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THE ROLE OF LIFESTYLE CHANGES IN LOW-EMISSIONS DEVELOPMENT STRATEGIES – THE CASE OF BRAZIL

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Orientadores: Emilio Lèbre La Rovere
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O PAPEL DAS MUDANÇAS DE ESTILO DE VIDA EM ESTRATÉGIAS DE DESENVOLVIMENTO DE BAIXAS EMISSÕES DE GASES DE EFEITO ESTUFA - O CASO DO BRASIL

Carolina Grottera

Março/ 2018

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Programa: Planejamento Energético

Esta tese discute como representar tendências relacionadas a renda, consumo e estilos de vida em projeções de longo prazo em países em desenvolvimento. Explora-se a interação entre convergência de renda e padrões de consumo, aspectos frequentemente negligenciados ou mal representados em exercícios de cenários. Questões metodológicas tratam da conciliação entre dados provenientes de pesquisas domiciliares, balanços energéticos e Contas Nacionais. A representação das preferências de consumo das famílias em um modelo de equilíbrio geral computável híbrido é discutida, seguida de uma aplicação para o Brasil. Esta pesquisa busca identificar em que medida uma maior consciência ambiental no consumo das famílias pode contribuir para a redução de emissões de gases de efeito estufa em 2050. Mudanças de comportamento relativas ao uso de energia, mobilidade, alimentação, demanda por bens duráveis e geração de resíduos são simuladas. Elas são contrastadas com um cenário de referência no qual o consumo das famílias é definido a partir de padrões e tendências vigentes. Esta tese apresenta e discute o impacto de mudanças de estilo de vida sobre o crescimento econômico, competitividade, geração de emprego, distribuição de renda, poder de compra e nível de consumo das famílias, entre outros. Mudanças estruturais decorrentes da transição são igualmente dignas de atenção. Este trabalho fornece recomendações para a implementação de estratégias de desenvolvimento de baixo carbono com objetivo de articular a agenda climática e outras prioridades socioeconômicas no Brasil.

Abstract of Thesis presented to COPPE/UFRJ as a partial fulfillment of the requirements for the degree of Doctor of Science (D.Sc.)

THE ROLE OF LIFESTYLE CHANGES IN LOW-EMISSIONS DEVELOPMENT STRATEGIES – THE CASE OF BRAZIL

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This thesis provides insights on how to adequately embark income, consumption and lifestyles trends in energy-economy long-term projections for developing countries. It focuses on income convergence and consumption patterns, often overlooked or misrepresented in scenario exercises. Methodological issues address the reconciliation of data from household surveys, energy balances and national accounts. The appropriate representation of household preferences in a hybrid computable general equilibrium framework is also discussed, followed by an application to the Brazilian case. The research seeks to identify to what extent increased environmental awareness on household consumption can contribute to reducing greenhouse gases emissions up to 2050. Behaviour shifts regarding energy, transport, food and durable goods consumption, as well as waste generation, are simulated. They are contrasted with a reference scenario in which household consumption is defined by current trends and standards. The thesis presents and discusses the impacts of lifestyle changes on economic growth, competitiveness, employment, income distribution, households` purchasing power and consumption levels, among others. The structural shifts that stem from the transition are also worthy of note. This work provides policy recommendations for low-emissions development strategies aiming at articulating climate objectives with other social and economic priorities in Brazil.

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Acronyms

AEEI - autonomous energy efficiency improvement

ANP – Agência Nacional do Petróleo, Gás Natural e Biocombustíveis

BECCS - Bio-energy with Carbon Capture and Storage

BEN – Balanço Energético Nacional

BRICS – Brazil, Russia, India, China and South Africa

BU – bottom-up

CCS - Carbon Capture and Storage

CEI – Contas Econômicas Integradas

CES – Constant Elasticities of Substitution

CGE – computable general equilibrium

CIRED - Centre International de Recherche sur l'Environnement et le Développement

COICOP - Classification of Individual Consumption According to Purpose

COP – Conference of the Parties

ECOPA - Evolution of Consumption Patterns, Economic Convergence and Carbon Footprint of Development - a Comparison Brazil – France

EPE – Empresa de Pesquisa Energética

EPPA - Emissions Prediction and Policy Analysis

GDP – Gross Domestic Product

GHG – greenhouse gases

GPS – Governmental Planning Scenario

GTAP - Global Trade Analysis Project

GWP – global warming potential

HDI – Human Development Index

IBGE - Instituto Brasileiro de Geografia e Estatística

ICET – information, communication and entertainment technology

IEA – International Energy Agency

IES 2050 – Implicações Sociais e Econômicas

IPAT – impact, population, affluence, technology

IPCC - Intergovernmental Panel on Climate Change

IPEA - Instituto de Pesquisa Econômica Aplicada

IPPU - Industrial Processes and Product Use

kcal - kilocalories

kWh – kilowatt-hour

LAV – linking aggregate variables

LDV – light-duty vehicle

LED - light-emitting diodes

LPG – liquefied petroleum gas

LULUCF - Land use, land use change and forestry

MAC – marginal abatement cost

MAPA - Ministério da Agricultura, Pecuária e Abastecimento

MCTIC - Ministério da Ciência, Tecnologia, Inovações e Comunicações

MIP – matriz insumo-produto

NAMA - Nationally Appropriate Mitigation Actions

NDC – Nationally Determined Contribution

OECD - Organisation for Economic Co-operation and Development

PNAD - Pesquisa Nacional por Amostra de Domicílios

PNE 2050 – Plano Nacional de Energia 2050

PNMC – Política Nacional de Mudança Climática

POF – Pesquisa de Orçamentos Familiares

PUC-Rio - Pontifícia Universidade Católica do Rio de Janeiro

RHG – representative household groups

SAM – social accounting matrix

SDG – sustainable development goals

SRES - Special Report on Emissions Scenarios

SSP - shared socioeconomic pathways

tCO_2e – ton of carbon dioxide equivalent

TD – top-down

TMC – total material consumption

toe – ton of oil equivalent

UN – United Nations

UNDP - United Nations Development Programme

UNFCCC - United Nations Framework Convention on Climate Change

US – United States

1 Introduction

Recent progress on the climate negotiations agenda succeeded in marking universal commitments as underlying to stabilize greenhouse gases emissions (GHG) at safe concentration levels. The Paris Agreement (UNFCCC, 2015), signed during the 21st Conference of Parties (COP21) in 2015, is the first climate initiative to place countries at the same level playing field. Contrary to previous endeavours such as the Kyoto Protocol, which acknowledged only developed countries were to take legally binding quantitative targets to limit their GHG emissions, parties are invited to adopt mitigation policies compatible with their own reality and development agenda through Nationally Determined Contributions (NDCs). In essence, this is the outcome of early attempts to encourage developing nations to embark in mitigation efforts, which emerged with the concept of "Nationally Appropriate Mitigation Actions" (NAMAs) (see UNFCCC (2007)).

The Paris Agreement determines that countries should seek to stabilize their emissions at levels consistent with limiting global temperature well below 2^{o}C above pre-industrial levels, ideally at 1.5^{o} C. However, current ongoing efforts, established in the countries' NDCs under the scope of the Paris Agreement are insufficient to reach such goals: if announced pledges are fully complied with, global emissions would still lead to a 3^{o}C temperature increase (UNEP, 2016).

As much as it is clear that higher ambition is needed, engaging in mitigation poses different set of challenges. Developed nations must benefit from the opportunities to reinvigorate their economies that transitioning to a low carbon society may offer (OECD, 2017). Emerging countries have to integrate the climate imperative into their development agenda: improving living standards and reducing inequalities. This means simultaneously decreasing the carbon footprint of consumption while supporting the middle class boom and meeting the basic needs of the poorest strata (GROTTERA *et al.*, 2015).

However, either climate or development goals will hardly be met without reconsidering traditional growth models that only yield slowdown in productivity growth and widening inequalities. Moreover, the fundamentals of continued economic growth are now at risk as the impacts of the current growth model on environment threaten the drivers of growth itself (OECD, 2017).

In this context, the Intergovernmental Panel on Climate Change (IPCC), in its Fifth Assessment Report (EDENHOFER *et al.*, 2014) calls for a new development paradigm. Rather than taking mitigation (and adaptation) from an isolate perspective, climate policy should be 'mainstreamed' into the broader concept of sustainable development, defined as 'development that meets the needs of the present without compromising the ability of future generations to meet their own' (WCED, 1987).

As argued by SHUKLA (2006 in SHUKLA *et al.* (2008)), a climate-centric vision would prove very expensive and might create a large mitigation and adaptation 'burden', whereas a sustainable development pathway could allow for lower mitigation costs and realizing co-benefits without sacrificing original objectives of economic growth and social development.

Most quantitative exercises on long-term stabilization scenarios fail to design consistent sustainable low carbon strategies, for they focus primarily in technical progress (EDENHOFER *et al.*, 2014) and mitigation takes place at the margin of 'business-as-usual' economic development frontiers. Some even rely on uncertain, incipient technologies such as Carbon Capture Storage (CCS) and Bio-Energy with Carbon Capture and Storage (BECCS). ROGELJ *et al.* (2011) provide a compilation of emission pathways from integrated assessment models consistent with a 2 °C global temperature limit. Recent initiatives however sought to envisage mindset transitions, by exploring different storylines with regard to technological development, natural resource deployment, institutional aspects, inequality trends, lifestyles, among others (BAUER *et al.*, 2017).

There is growing consensus that purely technological solutions are unlikely to fully deliver a transition towards a low-carbon society. BROWN AND VERGRAGT (2016) state that "while technological improvements in resource efficiency have slowed down the relentless growth in demand for materials, water and energy, they have not kept up with the growing demand, much less attain radical reductions in demand" (p. 308).

In particular, if emerging middle-classes in Asian and Africa mirror current western consumption patterns, possibilities of stabilizing GHG emissions at safe levels should narrow much quickly. The role of lifestyle changes has been increasingly pointed as an underlying lever to meet stabilization goals (DAI *et al.*, 2012; GIROD *et al.*, 2013b; TUKKER *et al.*, 2010). It has been acknowledged by the IPCC, as follows (EDENHOFER *et al.*, 2014):

"Behaviour, lifestyle, and culture have a considerable influence on energy use and associated emissions, with a high mitigation potential in some sectors, in particular when complementing technological and structural change (...) Emissions can be substantially lowered through: changes in consumption patterns (e. g., mobility demand and mode, energy use in households, choice of longer-lasting products); dietary change and reduction in food wastes; and change of lifestyle (e. g., stabilizing/lowering consumption in some of the most developed countries, sharing economy and other behavioural changes affecting activity)" (p. 20).

The mitigation potential of changes in consumption has received little attention in climate policy literature up to now (GIROD *et al.*, 2014), even if behavioural shifts may help attain emissions targets at lower costs (SCHANES *et al.*, 2016). Given the existence of various leverage points for lowering the carbon footprint of consumer behaviour and engendering more sustainable lifestyles, this thesis seeks to understand what role they can play in Brazil under the context of a climate-constrained world.

This study analyses three exploratory emissions scenarios for the whole Brazilian economy up to 2050, with a special focus on household income and consumption aspects.

In the reference scenario, the Brazilian NDC is put in place up to 2030, leading to emissions reduction compared to 2005 levels. With no extra official mitigation efforts from 2030 on, emissions resume and grow up to 2050. This is the base case scenario, even though it cannot be considered a 'business-as-usual' scenario, as current policies include mitigation efforts, even if modest ones.

A set of two alternative pathways is then tested. In the Lower GHG emissions lifestyle scenario, households pursue a more environmentally friendly behaviour:

healthier diets, with reduced meat consumption; prioritizing public and non-motorized transportation, instead of private cars; a broadened lifespan of goods such as clothes and appliances, and a more sound consumption of energy within the household. Households seek a less carbon-intensive, dematerialized lifestyle, prioritizing culture, education, and leisure over physical goods.

The third scenario, Lower GHG emission lifestyle scenario with increased trade, is similar to the previous one in terms of household behaviour. In this case, resource-intensive sectors seek to offset their reduced internal demand by boosting trade activity. The oil, liquid fuels, agriculture and industrial sectors manage to increase exports, due to international competitiveness.

The methodological framework used is the Imaclim-S BR model, a hybrid general computable equilibrium model which is a robust tool suitable for energy-economy-environment analyses. The application of Imaclim-S BR for this thesis` research objectives benefits from previous methodological efforts undertaken by WILLS (2013) and LEFÈVRE (2016).

The model is developed to assess the macroeconomic and social implications of climate policies in the medium and long term in a comparative statics fashion. It combines top-down and bottom-up approaches using a double accounting system in which both physical and economic flows are balanced. It comprises six energy sectors (Biomass, Oil, Coal, Natural Gas, Electricity and Petroleum Products), seven industrial sectors (Pulp and Paper, Steel, Non-ferrous Metals, Cement, Chemical Products, Mining and Other Industrial Sectors), apart from the Agriculture and Livestock, Transport and Services sectors, and represents the Brazilian economy for a 45-year period, from 2005 to 2050. The household sector is divided in ten income deciles, with household consumption and income levels calibrated using microdata from national household surveys. The outline of the expenditure and income formation profile of different income classes is the main contribution of this thesis for the continued efforts to improve the Brazilian national version of Imaclim-S.

The model's input-output framework allows for a comprehensive understanding of the effects of changing consumption in sectors demand level, prices, job creation and their feedback effects on governmental budget and households` income and consumption possibilities, GHG emissions, among others. Understanding how these variables should evolve is a key task for assessing the expected outcomes of environmental policies and regulations and support policy-makers decision process.

It is worthy to highlight that scenarios herein simulated do not aim at attaining GHG emissions levels consistent with a 1.5^{o}C or 2^{o}C target purely through behaviour shifts. Consumer strategies can only yield marginal GHG emissions reductions if no technological developments that lower the carbon intensity of products take place. Neither do they aim at modelling the whole of what would be a sustainable development pathway or a sustainable society. In such case, ground assumptions regarding trends in demography, urbanization and the role of Brazil in a globalized world would have to be reconsidered. This would divert from the comparative statics approach inherent to the Imaclim-S model framework. Rather, the ultimate goal of this study is to single out the effects of changing consumption patterns in the context of mitigation, and to discuss how they can complement and benefit from the required technological and structural changes. At last, they can serve as a starting point to the debate on what could indeed involve prospecting a sustainable society.

This thesis was developed under the scope of the ECOPA Project: 'Evolution of Consumption Patterns, Economic Convergence and Carbon Footprint of Development - a Comparison Brazil – France'. The project is a joint initiative coordinated by the Institute of Energy and Environment from University of São Paulo (IEE/USP) and Centre International de Recherche sur l'Environnement et le Développement (CIRED). It examines how flexible is the link between income and consumption patterns, by comparing household consumption in France, an "old" industrialized economy, and Brazil, a rapidly emerging economy. In both countries, a combination of econometric analysis of consumption data, household surveys and in-depth studies of representative goods and services is used to (i) map consumption patterns across income groups, (ii) explore the determinants of changes over time (iii) assess the energy and emissions implications of consumption patterns and (iv) draw implications for future GHG emissions scenarios. The fruitful discussions that took place along five years of close cooperation served as inspiration and benchmark for the pathways simulations.

This thesis is structured as follows: Chapter 2 performs a literature review on the investigation of income, energy use and GHG emissions convergence across countries.

It also presents the main determinants and future trends of household consumption. Drivers of change and consumer strategies for reducing GHG intensity of consumption are then discussed, together with a few empirical studies on the theme. Chapter 3 discusses the application of CGE models in long-term prospective scenarios exercises, with a special focus on adequately representing the household sector. Different techniques for assessing income and consumption are presented, followed by a brief discussion on labour markets. Chapter 4 introduces the Imaclim-S BR model, specially designed to assess climate and energy policies in Brazil. It details the hybridization process and the conciliation of microdata from national household surveys and the National Accounts framework. Modelling choices concerning aggregation (sectors, factors and institutional agents) and parameters (elasticities and wage curve) are presented. Chapter 5 is divided in two parts. Initial sections present the Brazilian context from a socioeconomic perspective and outline the country`s emissions profile. The Brazilian NDC is presented and discussed in a comprehensive context of development, though linkages with the Sustainable Development Goals (SDGs). The second part describes the scenarios exercises performed in this thesis, the main assumptions are discussed both qualitative and quantitatively for the reference and alternative pathways. In Chapter 6, the main results are presented. They focus mainly on economic implications, household consumption of various goods and services for different income classes and GHG emissions results. A brief comparison with studies undertaken in similar contexts is made, both in Brazil and for other countries. Finally, suggestions for further research are offered. Chapter 7 draws the main conclusions and policy implications of pursuing consumption patterns with lower emissions intensity in Brazil.

2 Income, consumption patterns and lifestyles: linkages and implications on energy and greenhouse gases emissions

2.1 Demographic trends, consumption and household energy requirements

Most low-emissions scenarios focus on technical fix possibilities to lower the carbon intensity of production (see ROGELJ *et al.* (2011)). However, one must not ignore that every good or service produced is destined to a final consumer after all. According to IVANOVA *et al.* (2016) global carbon footprint of household consumption accounted for 65% of world GHG emissions in 2007[1]. Direct emissions from fuel combustion for transport and household needs amounted 4.4Gt CO_2e, that is, 20% of the total 22Gt CO_2e. The largest share of associated emissions comes in the form of emissions embodied in goods and services. One of this study`s most astonishing results is how unevenly distributed per capita emissions are. While the world average is 3.4 tCO_2e per inhabitant, in some developed countries levels are more than five times greater than this, as it is the case of the United States (18.6 tCO_2e) and Australia (17.7 tCO_2e). In contrast, per capita levels in developing countries lie significantly below world average – Brazil and China have similar levels (1.8 tCO_2e), higher than India (0.8 tCO_2e), but lower than Mexico (3.8 tCO_2e) and South Africa (5.5 tCO_2e)[2].

In the past decades, demographic and economic growth in middle income countries led to unprecedented levels of global consumption and resulted in soaring GHG emissions. Future perspectives forecast ever-booming middle classes, whereas in the developed world consumption levels must keep increasing, even with declining demographic rates (GIROD *et al.*, 2013b)[3]. If the intrinsic past relation between per

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[1] The authors use EXIOBASE, an environmental-economic accounting framework gathering information for 43 countries, which account for approximately 89% of global gross domestic product (GDP).

[2] It is noteworthy to mention that, among the main novelties of this study, is the fact that it assigns the embodied emissions of imports to final consumers. This approach clearly depicts countries such as the United States as a net importer of GHG embodied in traded goods, whereas the opposite happens to China.

[3] See supplementary data for this study available at: http://iopscience.iop.org/article/10.1088/1748-

capita income and GHG emissions holds in the future, GHG concentration levels are unlikely to stabilize at safe levels (MOSS *et al.*, 2008).

In this context, examining how flexible is the link between income, consumption and GHG intensity is underlying. In other words, in which occasions one can expect middle-income countries to mimic the carbon-intensive lifestyles of developed nations, once they reach similar levels of income? In which occasions they are expected to take a different pathway, due to technological possibilities, social, cultural or other aspects? Understanding these dynamics allows for drawing plausible future emissions scenarios, as well as identifying where the best opportunities for reducing emissions lie.

This chapter provides an overview of income, consumption and GHG emissions related to household consumption. It is divided in three parts. Sections 2.2 and 2.3 discuss the relation between per capita income and emissions from a global viewpoint and explore the determinants of household consumption and the associated energy and carbon requirements. Sections 2.4 and 2.5 explore future trends in demography, economic growth and consumption, setting the basis for the discussions on changes towards less carbon-intensive consumption patterns in the rest of the chapter.

2.2 Convergence across countries, world trends in energy use and carbon emissions

The first inquiry to set the discussion is whether future prospects should anchor on the idea of converging patterns between developing and industrialized countries. Vast literature investigating the evolution of energy intensity of GDP predicates that, indeed, countries converge to a common level of energy intensity of GDP (usually using purchasing power parity indicators) (CORNILLIE; FANKHAUSER, 2004; MARKANDYA *et al.*, 2006; MIELNIK; GOLDEMBERG, 2000; NILSSON, 1992). Converging levels of CO_2 emissions for the past decade were also verified by EZCURRA (2007).

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However, many studies fail to contemplate the whole of embodied energy and emissions, as discussed below. In addition, as argued by NILSSON (1992), even if a correlation between energy use and income per capita exists, these cross-country comparisons can be misleading and inappropriate due to large differences in economic structure and climate, for instance. Indeed, when exploring future scenarios with a special focus on consumption, one should bear in mind the relevance of non-energy emissions from land-use and waste in emerging countries, for example. This should corroborate and extend the observation made by EZCURRA (2007) that the convergence process in emission levels that took place in the past (between 1960 and 1999 in his study) shall not continue indefinitely.

In fact, the neoclassical concept of per capita income convergence between developing and developed countries itself found in SOLOW (2000) has long been refuted. It was based on the idea that returns on capital in developing countries tend to increase above world average (boosted by savings and investment on productive capital), shifting resources from developed nations (for which rates of return on capital consequently decrease). Actually, convergence is verified only under certain conditions – ranging from savings rate to population growth[4]. Taking into account some complexity, such as human capital and technological transfers, seminal work from MANKIW *et al.* (1992) and BARRO AND SALA-I-MARTIN (1992) conclude that, rather than convergence, countries tend to reach different steady states.

Implications for GHG emissions levels both feed and unfold from this. TUKKER *et al.* (2010) mention the large-scale relocation of production from developed to developing countries. Less-efficient and obsolete technologies are deployed in the latter, where extraction activities and base industries dominate. In contrast, developed countries specialize in high technology and services.

This structural shift in industrialized countries fostered the environmental Kuznets curve hypothesis – the notion that cleaner production processes can be developed once a given level of standard of living is attained, allowing for a partial

[4] This is referred to as the “conditional convergence” hypothesis.

decoupling of GDP and pollution. However, as ROTHMAN (1998) postulates, this can be explained by the mere displacement of polluting industries to countries in early stages of development. He argues that "*what appear to be improvements in environmental quality may in reality be indicators of increased ability of consumers in wealthy nations to distance themselves from the environmental degradation associated with their consumption"* (p. 1).

The argument is reinforced by studies applying multi-region input–output models such as IVANOVA *et al.* (2016), PETERS *et al.* (2011), KANEMOTO *et al.* (2013) and WIEDMANN (2009)[5]. Emissions embodied in the growing imports from developing countries unveil the continued rise of the carbon footprint of wealthier nations. The success of some countries at stabilizing their emissions under the Kyoto Protocol may be revealed a fallacy if one takes a closer look at their supply-chain overall emissions.

All things considered, in the case of CO_2, emissions grow monotonically with income per capita (EZCURRA, 2007; RAVALLION *et al.*, 2000). Clearly, a global Kuznets curve hypothesis does not hold.

2.3 Determinants of household consumption, associated energy requirements and emissions

Attempts to imagine future consumption patterns based on past data and using fairly simplistic and aggregate indicators such as energy intensity of GDP or per capita emissions are insufficient, especially because the world is about to experience unprecedented levels of income, urbanization and trade activity. It is worthy to investigate what are the main drivers of household consumption and how they relate to lifestyle choices.

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[5] WEBER AND MATTHEWS (2008a) find similar results using household expenditure surveys and multi-country life cycle assessment techniques.

The broad concept of lifestyle goes further than sheer standard of living, which can usually be measured by socioeconomic and demographic indicators. LUTZENHISER AND GOSSARD (2000) define them as "*distinctive modes of existence that are accomplished by persons and groups through socially sanctioned and culturally intelligible patterns of action. (...) they distinguish social groups and "place" persons in the social landscape. They have a voluntary element, but are deeply engrained in habit, micro patterns of interaction and macro patterns of social possibility.*" (p. 215).

According to SANQUIST *et al.* (2012), this definition implies specific clusters of social, demographic and behavioural patterns that influence expenditures, consumption and use of energy. They define lifestyle as follows (p. 355):

> *"Lifestyle may be broadly conceptualized as patterns of consumption influenced by decisions at various points across the lifespan, such as what profession to engage in, where to live, when (or whether) to marry and have children, and more proximal choices regarding what to purchase and how and when to operate energy consuming equipment. This conceptualization suggests that analysis of lifestyle and energy consumption needs to encompass not only the traditional demographic segmentation elements, but also information about what people own and how they use it."*

In this sense, the next section gathers a small literature review on the main drivers of household demand. This understanding is underlying for the prediction of future trends on consumption and possible lifestyle shifts that may be adopted targeting a consumption profile less intensive in GHG emissions.

2.3.1 Explanatory variables of household demand – Energy and emissions requirements

Income is the main predictor of household consumption and its associate environmental impacts. Higher income allows consumers to use more energy and acquire larger volumes of material goods (TUKKER *et al.*, 2010). Lower income households usually spend a large share of their income in goods and services destined to meet their basic needs regarding food, shelter and mobility (usually public transportation). As income increases, expenditures are dedicated to durable goods such as clothes, appliances, etc. and various services (IVANOVA *et al.*, 2016). Naturally it also determines shifts within major consumption categories such as increased meat consumption and processed food, car and appliance ownership and the type of services people purchase (e.g. restaurants, cultural activities, etc.). TUKKER *et al.* (2010) and GIROD AND DE HAAN (2010) point out that richer households demand more lavish and superfluous products, or with better quality, so that the impacts per unit tend to be lower than those of goods designed to meet basic needs.

These phenomena are in line with a broad body of literature stating that energy requirements and carbon footprint grow in absolute terms, but less than proportionally with per capita income. IVANOVA *et al.* (2016) estimate that the carbon footprint increases by 66% as household expenditures double.

LENZEN (1998) finds that, although increasing in absolute terms, carbon requirements grow less intensively than energy requirements with increasing income. Similar results are present in KERKHOF *et al.* (2008), in which the authors extend the analysis for other sources of pollution (acidification increases proportionally to expenditures and smog formation more than proportionally).

UNDERWOOD AND ZAHRAN (2015) perform an input–output life-cycle assessment linked to household expenditure profile data for the United States. They find that direct energy uses (electricity, fuel for cooking and transportation) are more sharable than indirect energy uses, that is, the energy that is embodied in goods and services (such as food, appliances, etc.). As wealthier households spend a greater share of their income on less sharable indirect goods and services, per capita emissions rise with income. Analysing appliance usage specifically, MATSUMOTO (2016) finds that richer households tend to share less appliances, once members usually have their own individual ones (e.g. personal computer).

Household demographic characteristics also play a major role in defining consumption and environmental impacts, the main one being the number of members. This is due to the economies of scales that may arise from large households, given that needs grow with additional members, but generally less than proportionally. People living in the same household may share appliances and the energy required for cooking and thermal comfort (WEBER; MATTHEWS, 2008a). Members' age is also relevant. For instance, the presence of teenagers is related to higher electricity demand (due to higher rates of appliances ownership and the lack of energy savings behaviour) (GRØNHØJ; THØGERSEN, 2012; MATSUMOTO, 2016; MCLOUGHLIN *et al.*, 2012; THØGERSEN; GRØNHØJ, 2010). Retired and unemployed people may stay longer at home, also demanding more energy (MCLOUGHLIN *et al.*, 2012). Regarding other consumption categories, household structure and the presence of children also strongly influence car ownership rates and meal dynamics, for example. Gender, ethnicity, educational level and social security coverage also have explanatory power. JONES AND LOMAS (2016) perform a comprehensive review of household energy determinants, including **physical features** such as floor area, number of rooms, dwelling characteristics, tenure type, among others.

Household consumption is likely to vary significantly according to **location** as well. Residents from warmer regions do not require as much energy for heating as those from temperate zones (even though their thermal comfort needs may include space cooling). From an urban perspective, TUKKER *et al.* (2010) highlight that rural or suburban dwellings are generally larger than those in dense city centres. For this reason, and also due to higher insulation, they have higher thermal comfort requirements. In addition, people in low-density areas have high automobile dependency; they do not benefit of the high concentration of services and facilities present in urban centres.

Empirical research broadly confirms that expenditures related to dwelling, mobility and food are those accounting for the major environmental impacts associated to household consumption. Consolidated literature confirms these insights, despite significant variations owing to differences in scope and methodology. Many of these studies also indicate that energy and carbon requirements grow according to income, even though less than proportionally (COHEN *et al.*, 2005; IVANOVA *et al.*, 2016; LIU *et al.*, 2009; MOLL, H. C., NOORMAN, K.J., KOK, R., ENGSTROM, R., THRONE-HOLST, H., CLARK, 2005; NIDJAM, D.S., WILTING, H.C.,

GOEDKOOP, M.J., MADSEN, 2005; SPANGENBERG; LOREK, 2002; TUKKER *et al.*, 2010)[6].

2.4 Drivers and trends of global consumption up to 2050 and associate GHG emissions

Converging demographic trends can be observed across mostly all countries. Urban population is increasing fast, and by 2050, 66% of the world population (about 6.3 out of a total of 9.7 billion people) is expected to be living in cities (UN, 2015a). The greatest share of populational evolution is expected to take place in African and Asian countries, which should account for 7.8 billion people in 2050. Meanwhile, demographic rates slowdown in the rest of the world (UN, 2017).

However, declining fertility rates, later marriage and childbearing ages, as well as increasing divorce incidence, contribute to changing demographic profiles. These lead to a declining household size (LIU, 2013) and to the proliferation of single-person households. In addition, income gains, allow for the constitution of single-core households, rather than multi-generation ones.

The environmental implications of smaller and wealthier households are not negligible. According to UNDERWOOD AND ZAHRAN (2015), the social and economic development from which arise these socio-demographic trends produce countervailing forces; from one side, they enable energy efficiency improvements,

[6] At the individual level, some studies attempt to relate carachteristics to broad environmental awareness. SHAO *et al.* (2018) find that richer people in China have a higher ‘willingness to pay’ (WTP) for environmental protection, even though it also seems related to local environmental pollution degree. ZHAO *et al.* (2014) found that income is positively related to recycling behaviour, also in China. Findings from INSTITUTO AKATU (2013) show a positive correlation between social class in Brazil (measured by income) and environmentally-friendly behaviour, assessed through a ‘sustainable society index’ covering daily actions and overall perceptions on well-being. Conversely, LIOBIKIENE AND JUKNYS (2016), find that income does not have a significant influence on environmentally-friendly behaviour in Lithuania, whereas gender does (women tend to be more environmentally-friendly than men).

driving per capita energy and emissions downward. However, they also provide cost efficiency, decreasing the opportunity cost of cohabitation (rebound effect), eroding household scale economies and driving per capita emissions upward.

2.5 Future trends on global consumption

Global consumption levels are not expected to fully resemble current western patterns, even with similar levels of income. Apart from demographic shifts, technological improvements (and the possibility of leapfrogging), other social, cultural and religious aspects may play a role (e.g. religious restrictions on meat consumption). Still, GIROD *et al.* (2013b) project per capita emissions to grow steeply, especially because most of global population growth will occur in countries with current low per capita levels[7].

The global emissions intensity of food and mobility is expected to increase, due to a greater share of animal calories and faster and more energy-intensive transport modes. Miscellaneous goods also become more carbon-intensive, led by higher ownership rates of electronic devices and appliances. These products have high embodied emissions related to extraction and manufacturing processes (HERTWICH; ROUX, 2011 in GIROD *et al.* (2013); HISCHIER; REICHART, 2003 in GIROD *et al.* (2013)). In contrast, a lower GHG intensity for shelter is expected, given the moderate temperatures levels in these regions and consequent lower demand for household heating.

In a 9.7 billion people world[8] with booming middle classes and higher urbanization, per capita emissions in 2050 may range from 10.6 tCO_2e (in a rising emissions pathway) to 5.7 tCO_2e (in a stabilization without overshoot pathway). These estimates are found in GIROD *et al.* (2013b), based on the IPCC Representative

[7] According to RIBAS *et al.* (2017), the annual primary energy consumption average rate was lower than 15 GJ per capita in these countries, roughly fourteen times less than the average energy use in affluent countries.

[8] Prospects from UN (2017)

Concentrations Pathways (see MOSS *et al.* (2008)). The authors estimate that the GHG emission intensity of consumption has to be reduced by a factor of five compared to the rising pathway in 2050 to reach levels consistent with a 2◦C climate target (2.1 tCO_2e per capita in 2050[9]).

Regarding Total Material Consumption (TMC), NEUVONEN *et al.* (2014) establish an annual average of ten tons per capita of natural resource use to keep consumption levels within planet boundaries. Current levels in European Union countries range between 40 and 50 tonnes per inhabitant.

The remainder of this chapter focuses on consumption-based strategies aiming at lowering households` carbon footprint. Actions vary in their mitigation potential and degree of acceptability. An extensive literature review on low-carbon strategies for key consumption areas was performed, during which it was detected that studies using a CGE framework to assess their overall macroeconomic impacts are fairly scarce. In this sense, the following sections also attempt to discuss the main issues on simulating such behaviour shifts in CGE models.

2.6 Towards a mindset transition – Drivers of change

Consumption shifts towards a more environmentally-friendly and less carbon-intensive profile are not expected to take place organically in the coming decades, at least not at a game-changing extent. Current policies scenarios and storylines (assertively) do not take them into account. In fact, if they did, this thesis would by all means lose its purpose. Thereupon, a first inquiry on future scenarios targeting lifestyles less intensive on carbon emissions is whether they are feasible. If so, understanding what could realistically entail change is underlying.

One of the main drivers of transition is potentially the growing perception on the decoupling between material wealth and well-being. To put it differently, ever increasing consumption can hardly be followed by ever increasing satisfaction. Indeed,

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[9] See ROGELJ *et al.* (2011) and UNEP (2016).

material consumption is needed but once basic needs are comfortably met, consuming more tends to make little difference to subjective well-being. These findings are discussed by ABDALLAH *et al.* (2009), JACKSON (2009) and empirically supported by KAHNEMAN AND DEATON (2010). In this sense, consumption shifts could stem from the pursuit of a meaningful life, sustainable livelihoods, nonmaterial rewards of life and collective well-being in general – detrimental to pointless material consumption.

It is not the case to discuss in depth the subjectivities in the notion of well-being, but rather to leave it to be perceived under a broader sense. It is, however, worthy to make a quick digression on the shortcomings of GDP as an adequate measure of well-being. Briefly, the use of GDP aiming at quantifying well-being or development progress has been systematically criticised for its inability to encompass many dimensions of human development and of what consists a desirable society. It does not capture the value of non-monetized goods and services (e.g. air quality, ecosystem services, housework), ignores income distribution and environmental degradation and resource depletion, to name a few. It also fails at contemplating intergenerational aspects of exhaustible resource deployment (COSTANZA *et al.*, 2014; STIGLITZ *et al.*, 2009).

Efforts to develop alternative indicators either to replace or adjust GDP have been made. These approaches attempt to take social and environmental dimensions into account, rather than just economic aspects. Still, they stumble into data, reliability, comparability and adequacy issues. RIBAS *et al.* (2017) provide a compilation of such alternative options. The authors also point to the fact that, at least in developed nations, such indexes evolved alongside GDP up to the beginning of the 1980s, when they stabilize or decline, in spite of continued growth in GDP ((KUBISZEWSKI *et al.*, 2013 in RIBAS *et al.* (2017)). These findings indeed corroborate the notion of an existing threshold (relatively modest, according to TUKKER *et al.* (2010)), beyond which well-being levels cease to respond to economic growth.

Applying alternative indicators to quantify well-being is beyond the scope of this thesis, given the neoclassical approach of the chosen framework. It is nevertheless worthy to highlight that some of the identified issues are partially or fully addressed by the use of a dual-accounting framework, assessing both physical and monetary units. This will be further explored in Chapter 4.

Having said that, societal transition possibility comes from a reframing of the notion of well-being, towards dematerialized lifestyles, with people choosing to enrich themselves culturally, socially, spiritually, with a stronger sense of community. BROWN AND VERGRAGT (2016) argue that increased consciousness on resource limitation and the moral imperative of intergenerational solidarity will hardly be the main drivers of change.

Some authors claim that the world is doomed to lower consumption levels regardless of consumers` environmental awareness or willingness to change. In essence, elements that allowed the boom of hyperconsumption - near-full employment, easy credit, plentiful natural resource – are part of the past *(*BENNET AND O'REILLY (2010 in COHEN (2013)). COHEN (2013) puts it as follows (p. 43-44):

> *"The clear irony here is that while rapidly developing nations such as China, India, and Brazil are actively striving to develop their capacities for mass consumption, this macroeconomic model is breaking down in parts of the world where it first took hold.*
> *Though it may at times be difficult to conceive, change is ineluctable and despite the perception that we are tragically locked into lifestyles that are powerfully defined and delineated by consumerist rationales, new avenues will in due course avail themselves. (...) a high mass-consumption society is likely not the endpoint of history."*

Taking this into consideration, it would indeed be worthy to wonder if future scenarios grounded on boosted consumerism are plausible. The authors however seem to have a North-oriented viewpoint. They call for an involuntary reduction on consumption levels (tacitly, lower levels of collective well-being), imposed by austerity policies, deterioration of jobs, stagnated wages and ageing population, among others. This more likely to occur in countries that have reached advanced stages of industrialization and begin to suffer with such matters. COHEN (2013) mentions the case of Japan. PIKETTY (2014) also forecasts lower growth rates for these countries.

At least up to middle of the century, there is room for developing countries to grow, raise income and consumption levels (OECD, 2017). Therefore, focus should fall on the (voluntary) transition possibilities in these countries – in the case of this work, the Brazilian society.

2.7 Changing consumption patterns as a tool for climate policy

Considering changes in consumption as a climate policy tool may be relevant for a few reasons, apart from the synergies with a new societal paradigm discussed in the previous section. WYNES AND NICHOLAS (2017) point out the instant and widespread adoption possibilities of consumption shifts. GIROD *et al.* (2014) also highlight a few benefits, regarding competitiveness, carbon leakage and behavioural market failures. From a consumption perspective, all goods in the market are treated equally, regardless if they are imported or produced domestically. Possible competitiveness issues resulting from climate policies could be softened, contrary to a production perspective, in which economic instruments such as a carbon tax usually burdens domestic products in the absence of compensation mechanisms or border tax adjustments[10]. For this reason, consumption-related measures allow for embodied emissions to be tackled, diminishing carbon leakage possibilities (PETERS; HERTWICH, 2006). Finally, behavioural market failures can also be tackled. One example is the underestimation of energy savings enabled by more efficient appliances. Default products, standards and labels can guide consumers` choice through an untapped mitigation potential at low or even negative costs (ALLCOTT; MULLAINATHAN, 2010 in GIROD *et al.* (2014)).

However, when incorporating strategies related to consumer goods and services into input-output frameworks, the detailing level of various consumption categories is most likely foregone. For instance, households with higher income are expected to

[10] The authors also point that environmental taxes are usually levied almost exclusively on households and the transport sector. Industrial sectors are exempted precisely due to competitiveness issues (GIROD *et al.*, 2014).

demand higher-quality products and hence pay for a higher price (GIROD; DE HAAN, 2010). This is nevertheless hardly captured in National Accounts, which treat products homogeneously, at an aggregate level – an average quality level is assumed so that monetary flows may mistakenly overestimate quantities (and consequently energy and carbon intensities). Even if this issue is overcome through the use of a physical accounting method, as it is the case of hybrid models such as Imaclim-S BR, higher quality of products is inadequately expressed – it is partially constrained by existing income and technological levels in base year. The fact that more expensive goods usually have a longer lifetime (potentially lowering overall environmental impact) is not captured either.

The origin of products is also treated at an insufficient extent – products are taken as either domestically produced or imported. For domestic products, it is underlying to identify locally[11] produced and certified goods; otherwise their environmental impact will be overestimated. Analogously, the origin of imported goods also matters. The emissions intensity of similar products from different countries can vary significantly, reflecting differences in structure and efficiency of economies and in the product mix being produced (IVANOVA *et al.*, 2016). GIROD AND DE HAAN (2010 p. 43) exemplify:

> *"For nonfood products, the environmental performance of regional products is often better in OECD countries, because of more efficient production processes and stricter environment standards. For instance, production in China is more polluting, due to both an inefficient production system and a coal-dominated electricity supply* (PETERS; HERTWICH, 2006; WEBER *et al.*, 2008) *which leads to higher environmental impact per functional unit for cheap products from China."*

[11] A reduction in impact of up to 5% was found for U.S. households when consumers "buy local" (WEBER; MATTHEWS, 2008 in GIROD AND DE HAAN (2010)).

Competitiveness and carbon leakage related issues can be assessed using a multiregional input-output framework (see SU AND ANG (2011) and WIEDMANN (2009)), but not through a standard single-country one.

2.7.1 Lowering carbon-intensity at the household level through consumption shifts

This section discusses consumer strategies that can be pursued at the household level to lower carbon intensity, following a framework from existing literature. Options and challenges on how to incorporate them in a CGE framework are also explored.

Behavioural changes usually focus either on the type of goods consumed or on improving energy conservation practices. SCHANES *et al.* (2016) state that this is insufficient and "*in order to realise substantial reductions in emissions, it is crucial to think beyond well-known options and to seek new opportunities for emissions reduction*" (p. 2).

The authors propose a systematisation of behavioural options for end-users that bring about direct and indirect emissions reductions. They divide them into two major categories: (i) improvement, focusing rather on technological innovations; and (ii) reduction, that is, strategies that plead reductions in overall consumption levels, dematerialization, and lifestyle changes[12].

This section briefly describes such strategies, following their proposed framework, consolidating them in Table 2.1, where their integration into input-output analyses is discussed.

Direct reduction options include the reduced consumption of goods and services, for example, buying fewer clothes and rationalizing living space, and shifting household expenditures from resource-intensive products to less-emitting ones (e.g.

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[12] A similar categorization can be found in TUKKER *et al.* (2010). GIROD *et al.* (2014) quantify environmental impact of household consumption using the IPAT equation ('Impact, Population, Affluence, Technology').

spending less with private transportation and more with cultural and recreation activities). Energy-conservation measures in the use phase of products also falls under this category.

Efforts of such nature are effective at reducing emissions (DRUCKMAN *et al.*, 2011), but require fundamental change within daily life practices (SCHANES *et al.*, 2016).

Indirect reduction options also implicate deep transformations in daily habits and organisational structures. They involve alternative approaches to acquiring, using and disposing products (and services) aiming at indirectly reducing emissions (SCHANES *et al.*, 2016).

Changes in using behaviour allow users to relinquish ownership and seek the product or service whenever needed. They can do so either by renting (e.g. cars, libraries, clothes, etc., including peer-to-peer modalities), sharing (e.g. community laundries, toolsets) or product-pooling (simultaneous use by various users, e.g. carpooling through a collaborative lift system). Many of these possibilities function on a peer-to-peer basis. Often described as 'collaborative economy' or 'sharing economy', they are enabled by the diffusion of ubiquitous technologies, applications and increased connectivity.

A more intensive use of durable goods allows demand to be met with a smaller stock. The decreased overall demand for such goods contribute to reducing indirect emissions related to resource extraction, manufacturing and disposal (SCHANES *et al.*, 2016). However, TUKKER (2015 in SCHANES *et al.*) argues that a possible drawback is that they often lead to less careful user behaviour since the consumer no longer owns the product. This could lead to accelerating replacing rates.

Repairing, maintaining, reusing or donating goods, hence prolonging their lifespan, is another strategy that reduces emissions associated to the production of new goods. VAN NES AND CRAMER (2006) discuss the environmental desirability of longer lasting products. They are welcome when upstream impacts are heavy (e.g. resource or energy-intensive production process). When product replacement brings about efficiency gains during the use phase, as it is the case of newer household appliances, extending their lifetime may not be that interesting.

Lastly, initiatives that SCHANES *et al.* (2016) call “active consumership” (do-it-yourself, decentralized production) also decrease consumption indirectly, for they allow users to meet their needs without having to resort to traditional markets. Examples range from food production to on-site electricity generation and water reuse. They reduce environmental impact associated to load transportation, for example.

Direct improvement strategies consist in prioritizing the consumption of goods with lower embodied emissions or that enable a more efficient use phase (SCHANES *et al.*, 2016). Achieving efficiency during the production process may consist of deploying renewable energy or new techniques, but also relates to the many possibilities that stem from the so called ‘circular economy’, such as upcycling and industrial ecology systems. Advanced materials and digitalization also improve processes. However, these initiatives can be eventually criticized for not addressing overconsumption. DRUCKMAN *et al.* (2011) also alert for possible rebound effects.

Last, but not least, **indirect improvement** strategies refer to the indirect emissions reduction stemming from final consumers separating recyclable or reusable waste at the end of a product’s life (SCHANES *et al.*, 2016). This avoids new materials to be deployed in production processes (iron and steel, glass, textiles, organic waste) and avoid emissions from the extraction and processing of primary materials. It is noteworthy that industrial emissions relate both to energy use as well as the industrial process itself (IPPU); the latter can benefit enormously from this type of initiative.

Table 2.1 summarizes the above described strategies, classifying them according to the stage of product lifecycle they affect and discussing how they can be translated into an input-output framework for simulation purposes.

Some of the above strategies can be assessed quantitatively without much difficulty, namely those related to direct reduction. For example, energy conservation can be expressed through the percentual variation on energy final demand they entail. Analogously, some strategies related to direct improvement can be expressed in changes in technical coefficients in the interindustrial matrix (e.g. if users demand smaller or lighter vehicles, this lowers steel requirements by the light-duty vehicles production sector).

Others nevertheless can only be assessed implicitly. The aftermath of sharing economy strategies may require strong assumptions concerning the duration of product lifetime or avoided emissions related to transportation and resource-exploitation. In other cases, the level of disaggregation of national accounts – or even household surveys – may be insufficient. For instance, household appliances - efficient and inefficient ones - are treated aggregately.

Table 2.1 – Strategies for sustainable consumption

	Strategy	Example	Lifecycle stage	Integration on input-output framework
Direct reduction	Consumption reduction	Buy less clothes	Acquisition	Explicit Final demand
	Shift between consumption categories	Prioritize cultural activities rather than material goods	Acquisition	Explicit Final demand
	Curtailment	Turn lights off Adjust thermal comfort needs (heating or air conditioner)	Use	Explicit Final demand
Indirect reduction	Changes in using behaviour	Sharing, renting, pooling Repair, maintain	Use	Implicit Final demand
	Changes of consumption patterns	Reuse 'do-it-yourself'	Acquisition	Implicit Final demand
	Changes in disposal patterns	Donate Resell	Disposal	Implicit Final demand
Direct improvement	Purchase of efficiently produced products	Buy products that are locally produced or use renewable energy	Acquisition	Mostly explicit Intermediary consumption
	Purchase of products that are more efficient in use	Use efficient light bulbs and products with performance labels, certifications, etc.	Acquisition	Implicit Final demand
Indirect improvement	Changes in disposal behaviour	Recycle	Disposal	Implicit Intermediary consumption

Source: Author`s elaboration based on SCHANES *et al.* (2016)

2.7.2 Existing literature exploring behavioural shifts in household consumption

The contribution of consumption shifts to mitigation will depend on to what extent they can be implemented or, to put it another way, on their technical and social feasibility. A few empirical studies can provide a hint of what a “green” consumption pattern might look like, assessing how GHG or energy requirements vary across households with similar characteristics, such as income and expenditure levels or household composition.

GIROD AND DE HAAN (2009) compare the 10% of Swiss households with the highest GHG emissions per capita with the lowest 10%. They control the sample for expenditure level and household structure and find a range of 5 to 17 annual tons of CO_2e per capita. Low emitting households usually consume less meat and mobility and spend more on leisure, apart from paying higher price for better quality products (e.g. organic food).

ALFREDSSON (2004) simulates shifts in consumer behaviour regarding food, mobility and housing for Swedish households. He finds that GHG emissions decrease 20% in the short term and up to 40% in the long-run, even though rebound effects may be expected.

VRINGER AND BLOK (1995) compare energy requirements for households with similar income levels and find that the lowest decile consumes 22% below average, whereas the upper one demands 25% more than the average.

DIETZ *et al.* (2009) analyse 17 types of household action that can reduce energy consumption in US households, including both adoption of more efficient equipment and changes in use of equipment. They find that a reduction of 20% in households` emissions can be achieved within ten years if such actions are broadly adopted.

WYNES AND NICHOLAS (2017) estimate the emissions reducing potential of a broad range of individual actions, using various sources for developed nations. According to their study, actions with the highest impacts are having one fewer child (hence fully avoiding per capita emissions from one future individual[13]), living car free, avoiding one transatlantic flight, buying green energy, buying a more efficient car,

[13] The authors estimate that for a US family, having one fewer child would provide the same level of emissions reductions as 684 teenagers who recycle for the rest of their lives.

switching from electric car to car free and eating a plant-based diet. Actions with medium impact include washing clothes in cold water, recycling, hanging dry clothes, reducing overall consumption, eating less meat and eating locally harvested products. Actions such as minimizing waste and switching to more efficient light bulbs were found to have little impact on reducing annual per capita emissions.

Two studies use CGE modelling in order to assess dematerialization trends in household consumption. The simulations in DAI *et al.* (2012) are the closest to those performed in this thesis found in literature, given the methods, timeframe and objectives. The authors use a hybrid recursive CGE model to simulate different consumption patterns in Chinese households from 2005 to 2050, considering total expenditure increase and urbanization (and a larger share of household in final demand in 2050). They find that if households spent more on services and less on clothing, household furnishings and transport, 45 billion tons of CO_2 emissions would be avoided along the 45-year period. When a constrain in emissions is added, the carbon price in the dematerialized scenario falls by 13% compared to the materialistic one, reducing potential GDP losses that stem from taxation.

SHUKLA *et al.* (2008) compare a baseline scenario with conventional resource-intensive economic growth (and an unambitious, traditional carbon price policy) to two sets of low carbon pathways for India up to 2050. The low carbon scenarios assume equal cumulative CO_2 emissions. The first pathway (Carbon Tax) reproduces the baseline, with a more stringent stabilization target and higher carbon price. The second pathway (Sustainable Society) assumes broad societal transformations characterizing a shift to a new sustainable paradigm[14], either with or without explicit carbon pricing policies.

In the sustainable society scenario, individuals actively promote resource conservation (e.g. reduce, reuse, recycle), dematerialization, sustainable demographic transitions, urban planning, sustainable land use, efficient infrastructure choices, innovations and technology transfer. The new mindset presumes, for instance, lower demographic rates, as well as other different ground assumptions. Methodologically, it

[14] Similar to the IPCC SRES B1 global scenario (see NAKICENOVIC *et al.* (2000)).

is clear that this approach escapes the comparative statics dynamics, as the authors themselves explain (p. 160):

"The storyline of the 'sustainability' scenario therefore cannot be constructed by starting with the base case and making incremental changes."

It is nevertheless worthy and striking to compare how mitigation unfolds in the sustainability scenario compared to a pure carbon taxation policy - for the same level of emissions reduction. The carbon tax scenario relies on fuel switch in power generation and carbon capture and storage (CCS) accounting for almost 80% of total mitigation. In contrast, in the sustainability scenario, materials design and efficiency, reduced consumption, urban planning and modal shifts in transportation play major roles. Only 1% of the emissions reduction is met via CSS. Table 2.2 depicts all mitigation options for the two scenarios.

Table 2.2 - Contribution to mitigation in low carbon scenarios for India between 2005 and 2050 (billion tCO_2)

	Sustainable Society		**Carbon Tax**	
	10^9 tCO_2	**%**	**10^9 tCO_2**	**%**
Electricity (fuel switch)	13.4	21%	30.5	49%
Building (material design)	4.6	7%	–	0%
Renewable energy	6.2	10%	2.8	4%
Device efficiency	6.7	11%	5.9	9%
Material substitutions	4.9	8%	–	0%
Recycling	1	2%	–	0%
Reduced consumption	8	13%	–	0%
Urban planning	4.7	8%	–	0%
Transport (modal shift)	8.6	14%	–	0%
Others	3.8	6%	4.3	7%
CCS	0.5	1%	19.1	31%
Total mitigation	**62.6**	**100%**	**62.6**	**100%**

Source: SHUKLA *et al.* (2008)

2.7.3 Options for changes in consumption

This section explores the main trends in consumption, opportunities and challenges to reduce GHG intensity for the main consumption categories, setting the basis for the assumptions of the low-emitting scenarios described in Chapter 5. We highlight that not all of the options discussed below are simulated. Some still need technical developments or face economic and cultural barriers; others would require a comprehensive bottom-up assessment to be incorporated in a CGE framework.

Food

Diets with the highest GHG intensity are those with a high share of dairy and meat products in their composition, especially from ruminant animals. Consumption of processed food, highly correlated to income, also raises the carbon footprint of food consumption (IVANOVA *et al.*, 2016).

Cattle raising is a high-emitting activity due to enteric fermentation, fertilizers and land requirements (BUSTAMANTE *et al.*, 2012; GERBENS-LEENES; NONHEBEL, 2002; MERRY; SOARES-FILHO, 2017; VIEUX *et al.*, 2012). According to CASSIDY *et al.* (2013 in MERRY AND SOARES-FILHOS (2017)), 36% of all calories produced worldwide are destined for animal feed. These figures may increase with higher meat consumption levels in developing countries in the future. Cattle intensification will hardly deliver the required intensity reduction (MERRY; SOARES-FILHO, 2017), hence significant reduction in beef consumption will be needed (GIROD *et al.*, 2013b; MCALPINE *et al.*, 2009).

A shift towards more sustainable diets includes replacing meat calories from ruminant animals by non–ruminant (e.g. pork and poultry) and increasing the share of vegetables (BERNERS-LEE *et al.*, 2012; CARLSSON-KANYAMA; GONZÁLEZ, 2009; DE BOER *et al.*, 2016; HEDENUS *et al.*, 2014; HOOLOHAN *et al.*, 2013; MACDIARMID *et al.*, 2012; PERNOLLET *et al.*, 2017; STEHFEST *et al.*, 2009). Other radical options include meat produced *in vitro* and eating insects as a source of protein (ALEXANDER *et al.*, 2017; TUOMISTO; DE MATTOS, 2011). Some authors also highlight the health benefits of diets with reduced meat (DUCHIN, 2008; MACDIARMID *et al.*, 2012; MCMICHAEL *et al.*, 2007; VIEUX *et al.*, 2012).

Prioritizing local, seasonal and organic products and avoiding those produced in energy-intensive greenhouses also contribute to reducing the embedded energy from production and transportation (BLANKE; BURDICK, 2005; DE BOER *et al.*, 2016).

Shelter

Globally, heating accounts for the largest share of residential energy requirements. However, population and income growth in countries with moderate temperatures is likely to reflect on increased use of air conditioning (ISAAC; VAN VUUREN, 2009). Retrofitting, energy efficiency and low-emissions technologies in buildings must be implemented (GIROD *et al.*, 2013b).

Switching to renewable-generated electricity would be one of the main options to reduce GHG intensity of residential energy; some companies already offer the option for consumers to choose fossil-free electricity. This is especially relevant because per capita electricity consumption is expected to increase due to smaller households trends (JACQUOT, 2006) and growing appliance ownership in developing countries, where current rates are often still low (CABEZA *et al.*, 2018; RAO; UMMEL, 2017). Apart from income gains, flexible working patterns, online services, social network presence, etc. should boost the use of miscellaneous appliances related to Information, Communication and Entertainment Technology (ICET) (COLEMAN *et al.*, 2012; IEA, 2010).

The recent diffusion of fluorescent and light-emitting diodes (LED) bulbs has driven the energy-intensity of lighting down, but for other end-uses behavioural changes are still needed. Some individual choices include turning lights off whenever possible, unplugging appliances to avoid stand-by consumption, optimizing laundry activities through full loads or reduced temperatures, reducing bath duration and temperature, among others.

Mobility

Passenger transportation activity is expected to increase significantly in the coming decades (BAUER *et al.*, 2017), and is supposed to be one of the main drivers of oil demand (IEA, 2009).

SAGER *et al.* (2011), estimate that in order to keep concentration levels consistent with a 2^{o}C target, emissions related to light-duty vehicle use must decrease to levels that are currently experienced only by poor countries. However, developed nations standards are significantly higher and developing countries (e.g., India, Brazil and China) are rapidly motorizing (WRIGHT; FULTON, 2005). With few cost-effective measures, apart from social and institutional barriers, transportation is one of the most critical sectors concerning GHG emissions. The largest mitigation potential lies in technological development – especially because these apply also to load transportation. Nevertheless, changes in travel behaviour may also bring about climate benefits (See for instance GIROD *et al.* (2013a) and IEA (2009)).

Behaviour shifts in passenger transportation include different strategies. First, consumers may reduce their overall demand for mobility by avoiding trips when possible. This is enabled by the diffusion of online services and flexible working patterns, such as videoconferences and home-officing. For short trips, users can opt for non-motorized transportation (e.g. bicycles and walks). Another strategy includes prioritizing public transportation over private vehicles, considered the most cost-effective means to transport emissions reductions (WRIGHT; FULTON, 2005). According to CHESTER *et al.* (2013 in WYNES AND NICHOLAS (2017)), a switch to public transit has been shown to reduce emissions between 26% and 76%.

Evidently, substantial infrastructure investments are required for public transport modes, namely subways and urban trains (see GROTTERA *et al.* (2017) for an overview of the Brazilian context). Private vehicles remain the preferred option in many circumstances. In such cases, users should seek to reduce the energy requirements per transported passenger and increasing vehicle occupancy rates, by using smart mobility services (e.g. carpooling, car sharing). Alternatively, they can opt to use biofuels instead of fossil fuels and replace internal combustion engine vehicles by electric and hybrid ones.

Air travel is a critical case in the sense that there are no low-GHG technological prospections available (KIVITS *et al.*, 2010). As GIROD *et al.* (2013b) point out (p. 8):

> *"For air travel, the required GHG intensity seems unattainable; electrification is not possible, and hydrogen would be very costly because of the required storage volume and safety concerns (LEE et al., 2010). (...) the only realistic large scale technological option for 2050 is blending conventional fossil-based aviation fuels with biofuels. However, besides the limited potential of biofuels, the issue of non-energy related GHG emissions (KOLLMUSS, 2009) as well as embodied emissions from biofuels (DORNBURG et al., 2010) remain to be solved."*

High-speed trains may partially substitute domestic and continental flights (GIROD *et al.*, 2014), but for long-distance trips there is no alternative but a substantial decrease in demand to reach safe concentration levels.

Goods

The largest share of emissions related to goods stem from resource extraction and manufacturing processes. An increasing GHG intensity is expected due to the diffusion of ICET appliances (HERTWICH; ROUX, 2011). Options to reduce emissions from goods consumption include extending their lifetime through reusing, repairing, buying second-hand, recycling, etc. Possibilities to relinquish ownership stem from sharing economy alternatives. People can rent, lease or borrow goods they use only occasionally (e.g. tools, cameras, sport equipment, private vehicles for sporadic trips etc.) (BROWN; VERGRAGT, 2016).

Prioritizing goods made of certified, recycled and advanced materials, as well as locally manufactured, can also contribute to lowering embedded emissions. For energy-using goods, users must evaluate if replacing old items for more efficient ones is worthwhile.

Services

As for goods, most emissions related to services are embedded from upstream activities (buildings, transport, etc.). Nonetheless, this is the consumption category with the lowest average GHG intensity. According to SUH (2006), services account for less than 5% of direct emissions in the United States, and their emissions intensity per output is much lower than of physical products, even when supply-chain-induced emissions are included. GIROD AND DE HAAN (2009) find that consumers with low-emitting standards effectively spend a larger than average share of their budget on services (e.g. leisure). They argue that this has a double effect on eco-efficiency, for there are fewer resources available to be spent on GHG-intensive consumption categories, such as mobility. However, given the share of household budget devoted to services, total emissions are not negligible, on the contrary (IVANOVA *et al.*, 2016; SUH, 2006).

Greenhouse gases intensity across different types of services may vary significantly. Hotels are more carbon-intensive than education and health activities, for example. Hence, consumers seeking to reduce their carbon footprint should prioritize activities that are both energy extensive and labour intensive (GIROD *et al.*, 2013b).

2.7.4 Barriers to the adoption of lifestyles with lower GHG intensity

Shifts to consumption patterns with lower GHG intensity are constrained by social, cultural, technological and financial aspects. Apart from the lack of information and supply (e.g. low quality of public transportation in many cities in emerging countries), the following barriers are identified by GIROD *et al.* (2014):

- Consumer preferences: observed past trends in consumption reveal the strong predilection for carbon-intense products. This is the case of animal protein consumption in meals. Usually, the higher the income, the more beef replaces other types of meat with lower GHG intensity such as poultry and fish (see also DESJEUX (2012)). In transportation, one can mention air travel and the dominance of private vehicles even when public transportation options are available.

- Higher total costs (including capital, maintenance and operation costs): higher total prices discourage consumers to adopt sustainable practices. This is the case of sugar cane ethanol in Brazil, for which demand is positively correlated to final gasoline prices[15].

- Higher complexity: some options may require certain skills, including the necessary information for decision-making. This is the case of do-it-yourself practices, on-site farming or electricity generation (e.g. solar panels)

- Higher capital expenditure: for some options, consumers must cope with high upfront costs to benefit from lower running costs afterwards. Retrofitted buildings, solar panels and electric vehicles are a few examples. Lack of credit availability and long payback time aggravate consumers` willingness to adopt such options.

[15] Governmental interference in gasoline prices, recently put in place in Brazil aiming at keeping inflation rates under control, affects ethanol competitiveness, ultimately jeopardising the sector´s feasibility (see DEMCZUK AND PADULA (2017)).

3 Assessing household trends in long-term climate change research using computable general equilibrium models

3.1 Transformation pathways – where do we stand, what should we have in mind

The IPCC Special Report on Emissions Scenarios (SRES) (NAKICENOVIC *et al.*, 2000) is the seminal work consolidating existing scenario literature on greenhouse emissions concentration pathways. Different sets of scenarios are provided, representing consistent storylines with regard to demographic, social, economic, technological, and environmental development pathways.

On scenario methodology, SRES authors essay (p. 70):

> *"Scenarios are images of the future, or alternative futures. They are neither predictions nor forecasts. Rather, each scenario is one alternative image of how the future might unfold. A set of scenarios assists in the understanding of possible future developments of complex systems. (...) Scenarios can be viewed as a linking tool that integrates qualitative narratives or stories about the future and quantitative formulations based on formal modelling. As such they enhance our understanding of how systems work, behave and evolve."*

On the application of scenario methodology to assess greenhouse gas emissions pathways, the authors argue (p. 3):

> *"Future greenhouse gas (GHG) emissions are the product of very complex dynamic systems, determined by driving forces such as demographic development, socio-economic development, and technological change. Their future evolution is highly uncertain. Scenarios (...) are an appropriate tool with which to analyse how driving forces may influence future emission outcomes and to assess the associated uncertainties. They assist in climate change analysis, including climate modelling and the assessment of impacts, adaptation, and mitigation. The possibility that any single emissions path will occur as described in scenarios is highly uncertain."*

As pointed out by EBI *et al.* (EBI *et al.*, 2014), the SRES scenarios are outdated in terms of scientific understanding and in their demographic and socioeconomic assumptions. Indeed, new technological and energy trends, as well as the outcome of recent negotiations under the scope of the UNFCCC, must be taken into account. In addition, SRES scenarios did not set any specific mitigation goals, while recent literature pursues quantitative narratives linked to science-based climate objectives, often using a backcasting approach (DEEP DECARBONIZATION PATHWAYS PROJECT, 2015; UNEP, 2016).

More recently, a set of new pathways to assist climate modelling and integrated assessment models in general was developed, the Representative Concentration Pathways (RCPs), (VAN VUUREN *et al.*, 2011). They are complemented by future societal narratives, called Shared Socioeconomic Pathways (SSPs) (BAUER *et al.*, 2017; EBI *et al.*, 2014; MOSS *et al.*, 2010; O'NEILL *et al.*, 2017; VAN RUIJVEN *et al.*, 2014).

SSPs describe five different global futures in detail, providing trends for:

- Economy and lifestyle (globalization, consumption trends)
- Policies and institutions (effectiveness of national and international institutions, such as environmental and markets regulation)
- Technology (technological change, development of alternative energy sources)
- Environment and natural resources (constraint on burning fossil fuels, deployment of unconventional sources, degree of environmental degradation)
- Climate policy assumptions (adoption of carbon pricing policies)

The ideal model should be able to represent such aspects in a holistic way. However, as ROZENBERG *et al.* (2014) put it, not all drivers can be translated into input parameters (in fact some are direct inputs, some are the result of upstream assumptions and others are model outputs). Not all of them can be expressed in an explicit, quantitative way, but rather through a qualitative one. Notwithstanding difficulties in expressing a number of aspects, computable general equilibrium models (CGE) are a straightforward approach for meeting such needs. They are particularly adequate for assessing the macroeconomic and social implications of low carbon transition pathways.

The remainder of this chapter provides a brief overview on CGE models and their application under an environment-economic nexus context. Given the consolidated literature on this topic, we focus on techniques to represent income and consumption in such models, which is the core of this thesis. A few particular features of CGE models are better discussed in Chapter 4, when we present the specific methodology applied in this work, including the chosen methods for income and consumption analysis.

3.2 A tool for energy-environment-economy long-term assessments

The walrasian notion of general equilibrium, formalized in ARROW AND DEBREU (1954), gave birth to a class of macroeconomic accounting models seeking to better represent economy-wide dynamics. Computable general equilibrium models (CGE) emerged in the 1970`s (along with advancing computational skills) as more sophisticated versions of the traditional input-output models. These models adequately depict sectoral microeconomic structure, aggregating it to generate a complete set of macroeconomic variables (equivalent to National Accounts), containing an adequate specification of income and production flows (TOURINHO *et al.*, 2003).

Instead of fixed technical coefficient as in a pure Leontief framework, in CGE models the behaviour of agents is based on microeconomic foundations from neoclassical theory. In general, firms optimize profits, whereas consumers optimize utility.

Other neoclassical features include endogenous prices, full resource and capacity deployment, fixed proportions in input demand and linear cost functions, among others. However such properties do not account for the complexity of imperfect market conditions and ever-changing productive relations, among others. BUSSOLO *et al.* (2008) state (p. 63):

> *"CGE models are often criticized for imposing strong assumptions about the structure of an economy (for example, specific functional forms and closure rules) and for the results being largely determined by base year conditions and the*

chosen values for various elasticities (which, even when econometrically estimated, are susceptible to Lucas' 1976 critique[16])"

In conclusion, the lower the model`s ability to overcome the rigidity with which it represents substitution possibilities between inputs and factors, the less it is suitable for long-term comparative static analyses. This is especially true in energy-environment-economy prospective exercises, in which production and consumption relations (and others, such as investment decisions, technical change, etc.) are to be affected either by pure resource constraints, either by explicit carbon pricing policies.

WILLS (2013) discusses such limitation with an illustrative example. In the view of a climate policy that explicitly charges carbon emissions, a standard CGE model using a nested constant elasticity of substitution function (CES) would favour capital over energy, given the extra burden on energy costs. In a model heading towards an almost complete substitution between energy and capital, it would be possible, for example, to generate electricity virtually without energy, which is ultimately incompatible with natural laws.

The required technical realism in energy transition simulations can only come from a bottom-up analysis, able to precisely describe the competition of technologies both in the demand and supply sides based on expert data and to project radically different technology future with significant impacts on the environment. However highly sensitive from the technology point of view, the limitation of "conventional bottom-up" models is the poor macro and micro economic realism - a weakness in capturing indirect economic, environmental and social effects and to assess consumer and producer's behaviours in response to products' price changes (GHERSI; HOURCADE, 2006).

This is why the ideal framework must couple a bottom-up (BU) analysis and a top-down (TD), general equilibrium model, required to analyse the economy-wide

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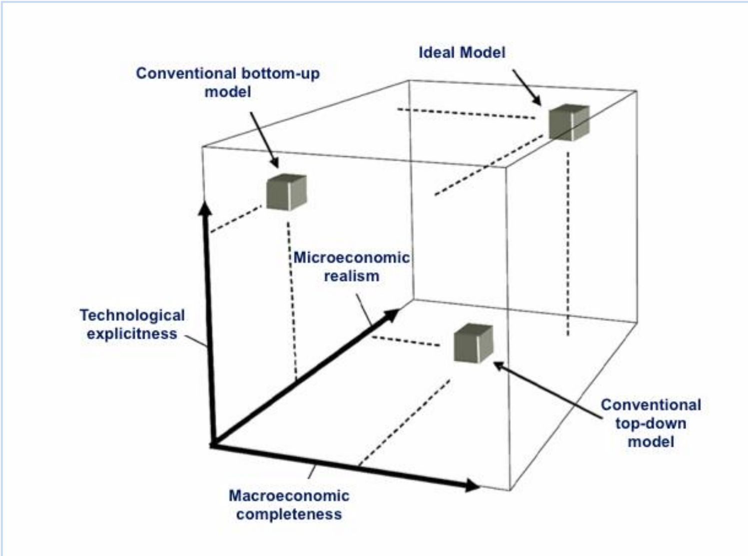
[16] LUCAS (1976) argues that conditions valid under given circumstances may no longer apply under others and, as a consequence, one cannot predict the effects of economic policies entirely upon relationships observed in the past.

impacts of transition pathways. HOURCADE *et al.* (2006) portray the ideal modelling framework, incorporating "microeconomic realism", "macroeconomic completeness" and "technological explicitness" in the figure below.

Figure 3.1 - Three-dimensional assessment of energy-economy models



Source: HOURCADE *et al.* (2006)

The next chapter discusses to what extent the Imaclim-S model`s features meet such requirements. Following a brief literature review on CGE models applied for climate policy research in Brazil, the remainder of this chapter discusses how to adequately represent households and labour supply in CGE models, a greater contribution of this thesis. These aspects will also be revisited in the following chapter, when we combine the exposed theory and the methodology applied in the model calibration.

3.3 Applications of CGE models for climate policy research in Brazil

Early applications of CGE model aiming at assessing mitigation impacts in Brazil date from the 2000s. TOURINHO *et al.* (2003), GUILHOTO *et al.* (2002) and LOPES (2003) are a few examples.

Using a static CGE model, TOURINHO *et al.* (2003) test three different levels of tax on burning fossil fuels (from US$3 to US$20) for the Brazilian economy in 1998. Their exercise is rather experimental, exploring the model`s ability to assess climate policies by coherent outcomes. Indeed, results indicate a shift from resource-intensive sectors to less intensive ones and corresponding variations on price levels and slight losses in GDP contrasted with a heavier burden on household income. Evidently, GHG emissions decrease.

FEIJÓ AND PORTO JUNIOR (2009) also perform an one-year analysis using GTAP-E[17] to evaluate welfare and environmental impacts of Kyoto Protocol pledges in Brazil, considering the country takes part in flexibility mechanisms established by the agreement.

Subsequent applications attempted to include other sources of GHG rather than burning fossil fuels, such as land-use. GURGEL AND PALTSEV (2014) use the EPPA[18] model, a dynamic recursive CGE described in PALTSEV *et al.* (2005). This is a global model in which Brazil is one of the regions, and it accounts for land competition. They test different ways to achieve Copenhagen pledges established in the PNMC[19] (extended up to 2030), through various set of articulation among sectors (land-use, agriculture, energy, etc.), all of them including carbon pricing mechanisms (endogenously defined sectoral taxes or emissions trading schemes). Results show that the most cost-effective option is by far reducing emissions from deforestation. This could be achieved with low tax levels (no more than US$3/t$CO_2$e) and negligible GDP losses. The authors however inquiry on the feasibility of applying a tax on deforestation, given high monitoring and enforcement costs (also pointed out by GROTTERA *et al.* (2015)). In the case of taxing emissions from agriculture and energy as well, a universal carbon price would prove more cost-effective than sectoral taxes.

Similar findings regarding the mitigation potential of reducing deforestation are found in CHEN *et al.* (2013). They also use a recursive dynamic CGE model to assess

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[17] Global Trade Analysis Project - Energy

[18] Emissions Prediction and Policy Analysis

[19] Acronym in Portuguese for National Policy on Climate Change

the compliance of the PNMC, extended up to 2040. The largest the failure at curbing deforestation, the highest is the economic cost of achieving emissions reduction, given that a significant amount of mitigation from energy use and industrial processes would be required. This would also reflect on higher carbon tax levels. Different options for recycling carbon tax revenues are tested: lump-sum transfer to households, financing wind energy and cut in labour taxes. If the latter is chosen, a double-dividend would be possible, simultaneously reducing emissions and increasing GDP.

While studies conducted by GURGEL AND PALTSEV (2014) and CHEN *et al.* (2013) stand out for their recursive nature and for contemplating non-energy emissions, they fall short of representing agents` response to a price on GHG emissions at the sectoral level. DE GOUVELLO *et al.* (2010) manage to asses sectoral technological change and mitigation potential for Brazil in the long-run with reasonable financial and technical realism by using sectoral mitigation abatement cost curves (MACC) and discount rates. In contrast, they fail to represent it a CGE framework (contrary to MCTIC BRASIL (2018), in which the integration of MACCs in a macroeconomic model allows for assessing a few aggregates, such as GDP, sectoral output, wage levels, among others).

Other shortcoming of most CGE models used for Brazil is the aggregate representation of the household sector, preventing from adequately assessing distributional impacts of climate policies. MAGALHÃES AND DOMINGUES (2013) develop the first documented CGE model to split households into income classes. In their model, households are represented in ten representative household deciles, similar to what is performed in this thesis. They show that the bottom decile spends 5.2% of its budget on energy, being 4.1% on electricity, whereas the top decile spends 9.4%, being 5.5% on gasoline and only 1.6% on electricity. Therefore, from a distributional point of view, policies that exempt electricity and burden gasoline would be preferable.

In brief, models have their own strengths and shortcomings, and recent progress has and will increasingly make CGE a suitable tool for effective climate policy analysis. For instance, the long-term scenarios in LA ROVERE *et al.* (2016) using Imaclim-S BR are the first to simultaneously embark MAC curves and disaggregate households into different income classes – adding technical realism and enriching socioeconomic analysis. Recent exercises using the Imaclim framework for Brazil are presented in section 4.2.4.

3.4 Techniques for assessing income and consumption in CGE modelling

Literature on the effects of economics policies and reforms on income distribution and poverty is extensive and somewhat consolidated (BOURGUIGNON *et al.*, 2008; BOURGUIGNON; PEREIRA DA SILVA, 2003).

Applications range from carbon pricing (BRENNER *et al.*, 2007; GONZALEZ, 2012; LA ROVERE *et al.*, 2015, 2016; LEFÈVRE *et al.*, 2018), tax structure (SAHN; YOUNGER, 2003), public expenditures (DEMERY, 2003; VAN DE WALLE, 2003), trade reforms (HERTEL, 2004; RAVALLION; LOKSHIN, 2008) and labour-related issues (MACHADO; RIBAS, 2010), among many others.

Still, those who undertake these kinds of assessments face lack of data availability and robustness, computational limitations, apart from modelling issues. A major challenge is how to represent the behaviour of heterogeneous classes of agents. The applied technique must be chosen accordingly, taking into consideration the issues above mentioned.

BOURGUIGNON *et al.* (2008) present different ways of performing such analyses through "macro-micro" techniques, that is, combinations of macroeconomic and microeconomic frameworks that deal with agent behaviour. With different degrees of integration, these techniques identify the effects of macroeconomic policies (such as trade, exchange, fiscal reforms, among others) on agents at a microeconomic level and thus investigate the second order effects of measures. VAN RUIJVEN *et al.* (2015) provide a broad review of these techniques applications and their suitability for long-term climate change research.

This section discusses the main topics related to representing the household sector to model the effects of economic policies on income distribution and poverty. We focus on computable general equilibrium models (CGE), for which a small literature review is performed.

3.4.1 Representative Household Groups

The first class of models uses the so called Representative Household Groups (RHGs). They are therefore known as the SAM-CGE/RHG models, since they are directly incorporated to a Social Accounting Matrix framework.

The use of RHGs consists of separating the population into representative groups within a CGE model, each group being represented by a virtual household that behaves as the group average, in order to capture how certain policies affect them. The level of aggregation defines the aggregate behaviour, in terms of factor endowment (labour supply and level of remuneration, income on capital), consumption preferences and savings.

It should be noted that groups are not necessarily defined according to income, they may follow other criteria, such as racial classes, geographic location, qualification of the workforce, etc. (DAVIES, 2009).

One of the main limitations of using RHGs is that the distribution of income within groups is exogenous, that is, this approach is able to capture only variations between representative groups. BOURGUIGNON *et al.* (2008) explain (p. 11):

> *"Strong assumptions must be made: the distribution of relative income within each RHG is policy-neutral, that is, it is not affected by any change in macroeconomic policy; and the demographic weight of households in each RHG is constant. Hence, this approach essentially focuses on changes in the distribution between RHGs."*

SAVARD (2003) also points that, because parameters reflect the aggregate behaviour and not necessarily the average behaviour, the behaviour of a specific group is biased towards the richest in the group. As they are the ones endowed with most of the factors, their behaviour likely dominates.

Examples in which this methodology is employed are ADELMAND AND ROBINSON (1978) and AGÉNOR AND JENSEN (2007). Others apply it specifically for testing carbon pricing policies. YUSUF AND RESOSUDARMO (2015) apply a fairly large number of RHG (100 urban and 100 rural) to test a carbon tax on a static CGE model. They find that recycling carbon revenues by reducing sales taxes may soften the adverse effect of output loss, whereas a lump-sum transfer to households is the most progressive option (these results are correlate to the ones in GROTTERA *et al.* (2015), but in their case exemptions fall on labour taxes).

RAUSCH *et al.* (2011) depart from a sample of more than 15 thousand American households and endogenously integrate them in a static general equilibrium model (USREP). They test a carbon pricing scheme with different revenue recycling options (lower tax rates on income, per capita lump-sum transfer and lump-sum transfer proportional to capital income). They combine the sample into different sets of representative groups: in income deciles, by ethnical group and by region. The authors alert for variations in impacts within broad socioeconomic groups that may swamp average variation across groups.

3.4.2 Linking Aggregate Variables

A second class of models includes using a specific household module coupled with the CGE core. It operates sequentially in two steps: (1) the top-down model (CGE) is used and (2) the solution in terms of price, wage, and employment vectors - the so-called Linking Aggregate Variables (LAVs) – feed the bottom-up module that represents households.

It includes as many "representative households" as there are actual households in the survey, considering all the observed heterogeneity of the population of households (BOURGUIGNON *et al.*, 2008). Examples of applications are CORORATON (2003) and DECALUWÉ *et al.* (1999).

The main advantages of this approach compared to the previous one are the fact that it allows for intra-group income distributional changes and it that exempts the modeller of having to select aggregation criteria. Also, they allow to represent shifts in demographic structures in long-term projections, by reweighting the sample size of given population groups (e.g. urban/rural, age, educational level, etc.) (VAN RUIJVEN *et al.,* 2015).

However, data conciliation may pose a challenge, due to difficulties on the definition of aggregate goods and services to be used in both micro (household expenditure) and macro (sectoral production) sides of the model (SAVARD, 2003). Under or overreporting issues on household surveys may also arise (FERREIRA *et al.*, 2008b).

When only first-round effects are assessed, disregarding second-round effects that stem from behavioural reactions, the approach is designated as 'micro-accounting'. When responsive behaviour regarding prices and wages variation - for example through households altering goods and services demand or labour supply and time allocation choices – it is designated as 'micro-simulation'. They are described in more detail next.

3.4.2.1 Micro-accounting

In this approach the result generates a one-time shock in the microeconomic module. Households do not respond to price shocks by changing the amount of factors (labour, capital) they offer or the quantity of goods and services they demand.

RAVALLION AND LOKSHIN (2008) simulate a policy of reducing protectionism in cereal trade in Morocco. They analyse the direct and indirect effects on prices of goods. However, they assess only first-order effects, that is, through a sequential, not an integrated approach. They do not capture the dynamic effects of the reform on labour markets and technological innovation or environmental gains. In the model, household class has a utility and a production function, which vary according to a vector of prices and wages. The impact on prices is given, that is, the first order effect on welfare is calculated by adding the changes proportionally to what they represent in relation to initial expenses or incomes. The authors find small impacts on average consumption and inequality, and conclude that the poorer rural population is impaired by being a net consumer (i.e. consuming more than producing) of cereals, a sector in which the effect is obviously more intense.

BUSSOLO *et al.* (2008) integrate the global static CGE model LINKAGE (World Bank, GTAP) with household profile surveys for Brazil, Chile, Colombia and Mexico in order to estimate the first order effects of trade liberalization policies on poor households. The model is connected to the household module through the following variables: real average wage in four segments of the labour market (skilled/non-skilled, agricultural/non-agricultural), average real income of capital of non-agricultural sector, average real income of capital and land of agricultural sector, and relative prices between agricultural and non-agricultural commodities. The change in real household income is calculated by applying the changes in income to household endowments. Results show that, due to very different initial positions regarding economic structure, poverty levels and trade protectionism, the effects vary widely across countries. In general, they conclude that distributional effects are more relevant than those on economic growth. In the case of Brazil, rural poor are less impaired than urban ones, since protectionism over agricultural goods in the reference scenario was low, unlike the manufactured goods.

These two studies use the micro-accounting technique, and demonstrate its ability to capture the overall effects of policies and reforms, as well as ease of implementation. On the other hand, it is clear that this type of methodology should be used exclusively to evaluate short and medium term effects.

Even though first order effects are generally a good approximation of the total impact in cases of marginal changes and under the assumption of competitive markets, BOURGUIGNON AND SPADARO (2006) and HERTEL AND REIMER (2005) point to the fact that it may not be negligible at the macroeconomic level. In the case of policies geared specifically to households, such as income transfer programs, it is highly recommended that their responsive behaviour be taken into account.

Applications in climate-related research include BUDDELMEYER *et al.* (2012) (mitigation scenarios) and HERTEL *et al.* (2010) (impacts on climate change on crop yields).

3.4.2.2 Micro-simulation

In this approach, generally referred to as MSS (Sequential Microsimulation), an econometric model provides behavioural reactions used to simulate changes in wages, autonomous incomes, employment situation, etc. The top-down model provides information to the bottom-up module that allows to understand how households react to the variations generated by policies at first. The main limitation of this approach is that the instruments for the simulation are limited by the amount of LAVs.

ROBILLIARD *et al.* (2008) integrate a CGE model with a behavioural simulation module to analyse the impacts of the 1997 financial crisis in Indonesia on income inequality and poverty. Their results show that, although the incomes of the rural and urban classes converge in the final balance of the crisis, inequality worsens due to income divergences between these classes.

FERREIRA *et al.* (2008a) use a top-down model for the Brazilian economy to analyse the impacts of the 1999 exchange rate crisis on the occupational structure of labour and income distribution. They compare the results of a simulation with actual past data. Unlike other studies above mentioned, the authors do not use a computable general equilibrium framework, but rather an IS-LM model (Investment Savings and Liquidity Preference Money Supply) estimated econometrically by time series. Integration with the household module is performed through LAVs. Results point to a drop in real income for all strata, as well as a generalized increase in poverty. As the reduction in income was higher for the higher classes, income inequality decreases. Unemployment, especially among the urban and wealthier classes, increases. The econometric model, although flawed in some aspects, predicts fairly well changes in household income.

In short, the main difference between the micro-accounting model and the micro-simulation approaches is that the latter is valid in cases where the ‘Envelope Theorem’ is not applicable, for example when policies affect decision to take part in the workforce, or when imperfect market conditions apply (e.g. resource rationing).

3.4.3 Integrated Multihousehold

Finally, an even more detailed analysis, promoting the best use of data at the micro level, consists of a CGE model fully integrated with the microeconomic household module. Unlike the previously described approaches, the Integrated Multihousehold technique contemplates the full interaction between top-down and bottom-up modules, beyond first and second order effects. A series of iterations is performed until convergence is achieved. It can be roughly assumed that MSS would be the first iteration of an IMH model. The greatest challenge in this type of approach is clearly the operationalization of an immense data volume. This type of approach can be found in HECKMAN *et al.* (1998) and TOWNSEND AND UEDA (2006).

BOURGUIGNON AND SAVARD (2008) use this methodology to analyse the distributional effects of a trade reform in the Philippines. In their model, the top-down and bottom-up modules communicate through the following linking variables:

- Consumption and supply of labour (exogenous in CGE, endogenous in the household module);
- Wages and prices (exogenous in the household module, endogenous in CGE)

The authors propose a sophisticated way of representing the labour market, dividing it into formal and informal (they highlight salary rigidity in the formal market), and allowing to relax the assumption of a perfectly competitive market. One of the limitations of this study, however, is that the authors use the same income elasticity of demand for all goods, as well as the same Frisch parameter[20].

Comparing the complete iteration exercise to a MSS simulation, the authors conclude that results are not very dissimilar, as long as rigidity in the labour market is low. Under the assumption of flexible prices, the MSS provides a reasonable approximation of what the results would be like in the fully integrated model.

Given that most household data come from household surveys that escape the National Accounts framework, a brief discussion on two topics is welcome: section 3.5 discusses inconsistencies between macroeconomic data and sample surveys and how they are overcome in this study and section 3.6 presents criteria for taking into account economies of scale in household consumption.

[20] The Frisch parameter captures the elasticity of labour supply relative to wage level.

3.5 Usual inconsistencies between macroeconomic data and sample surveys

Combining macro and micro models implies working with different types of data sources, including national accounts and primary surveys, which are notoriously inconsistent (BOURGUIGNON *et al.*, 2008). DEATON (2004) identifies some reasons for such discrepancies: apart from conceptual and nomenclatures matters, national accounts, in contrast to sample surveys, are more likely to capture larger transactions than smaller ones. STIGLITZ *et al.* (2009) call for huge discrepancies between households surveys and GDP levels. ROBILLIARD *et al.* (2008) report survey income to be, on average, less than 60 percent of GDP. NERI (2011) finds that, between 2003 and 2009, GPD per capita growth captured in Brazilian National Accounts is 17.3%, whereas when measured through PNAD[21], it increased 32.3%. He adds a caveat explaining that the two indicators tend to converge in the long-run.

Yet, due to their deep level of detailment, household surveys are a much more adequate and reliable source for household income and consumption assessment. One modelling option consists of applying the existing relations in household surveys proportionally to the National Accounts framework, that is, keeping its final figures unchanged. Otherwise, one risks jeopardizing macroeconomic consistency (ROBILLIARD; ROBINSON, 2003).

3.6 Accounting for households` structure - Economies of scale in household consumption

Household consumption and welfare analysis often consider per capita expenditures or per capita income as indicators. Nonetheless, such approach fails at taking into account potential economies of scale that may arise from cohabitation.

Households` needs grow with each additional member, but generally not in a proportional way. For example, a household comprising three people would normally need to consume more than a lone-person household, but not three times more, for them

[21] Acronym for ‘Pesquisa Nacional por Amostra de Domicílios’.

to enjoy the same level of well-being (OECD, 2013a). People living in the same household may share, to a certain extent, appliances (washing machine, television set, refrigerator, etc.), furniture, as well as room lighting and heating or cooling. The size of the household and the level of fuel required for private transportation do not grow proportionally to the number of additional members in the household either.

On the other hand, some goods and services are less subject to be shared among individuals. People need their own amount of food and clothing. Public transportation, generally consumed at a one-person-one-ride basis, is also less likely to allow for economies of scale.

The type of goods mentioned above are the so-called “rival goods”, that is goods (and services) whose consumption by one person prevents simultaneous consumption by others (VARIAN, 1992). Rivalry is measured in a continuum: a slice of pizza is a complete rival good, since once eaten by a person, it cannot be eaten by anyone else. On the other hand, an internet video is a complete non-rival good, since it can be enjoyed simultaneously by as many people as possible (even though the computer and the internet connection required to do so are to a certain level rival goods). Roads or public illumination networks are almost non-rival goods: they can be enjoyed by many consumers, until saturation is reached.

Consumption profiles vary across households from different levels of income. Lower income households tend to spend proportionally larger share of their income to meet basic needs, that is, in food, clothing, hygiene items, etc., which are generally rival goods. Wealthier households spend a smaller share of total income on these types of goods, and can afford to buy shareable ones, such as appliances, as well as goods and services related to leisure and culture. Therefore, the likelihood of reaching economies of scale is expected to grow according to household income.

In order to make welfare comparisons across households of different sizes and compositions, it is important to take the possibilities of economies of scale into account (DE REE *et al.*, 2013). Equivalence scales adjust the incomes of households in a way that recognizes differences in the needs of individuals and the economies that arise from sharing resources. The variables that are usually taken into account are the size of the household and the age of its members, that is, whether they are adult or children (OECD, 2013b). The most commonly used equivalence scales are OECD (2013b):

- **OECD equivalence scale (or "old OECD scale"):** first proposed by OECD (1982), it assigns a value of 1 to the first household member, of 0.7 to each additional adult and of 0.5 to each child;

- **OECD-modified scale:** first proposed by HAGENAARS *et al.* (1994), after a series of revisions of the old OECD scale, it assigns a value of 1 to the household head, of 0.5 to each additional adult member, and of 0.3 to each child;

- **Square root scale:** recent OECD publications use a scale which divides household income by the square root of household size, regardless of the members' age. This implies that, for instance, the needs of a household of four persons are twice as great as those of a single-person household.

Modelling and metrics choices may bring about uneven results, and deliver different policy implications, including when it comes to income distribution and inequality (JOHNSON; SMEEDING, 2015).

GIROD AND DE HAAN (2010) perform and in-depth analysis of the consumption mix of Swiss households according to their level of income. They compare the allocation of GHG emissions to monetary versus functional units (physical quantities or suitable proxies). They find that the elasticity of GHG emissions with expenditure is lower if the 'new OECD scale' is applied to household income compared to an estimation without such correction.

GRAINGER AND KOLSTAD (2009) test the distributional effects of a carbon tax ranking households comparing the annual versus lifetime income approaches. Besides, they compare the results using household and equivalence scale bases. The authors find that the use of household equivalence scales can exacerbate the regressivity of carbon pricing (also suggested by GROTTERA *et al.* (2016a)). The degree of regressivity depends on the income measure used:

"On an annual basis, a carbon price is two to three times more regressive than on a lifetime basis (i.e. using annual expenditures). When examining the policy on a per-capita basis with equivalence scales, a carbon price is roughly twice as regressive than at the household level. In each case the regressivity is largely driven by direct energy consumption" (p. 18).

3.7 How do consumption patterns change as household income rises?

When income rises, saturation occurs for virtually every consumption category, but this is evidently more prominent for basic goods and services, such as food and energy services (MONETA; CHAI, 2014). Therefore, using income elasticities calculated from past data in long-term scenarios is not adequate, for they cannot capture such saturation thresholds. When applying them, one incurs the risk of overestimating consumption for normal goods and services present in past consumption baskets used in calculations.

At the same time, they cannot foresee consumption 'leaps' either, that is, when certain goods and services enter the consumption basket once a given level of income is attained (e.g. the purchase of a private vehicle). In this case, one risks underestimating consumption for such goods and services.

It is clear that this would be subject to Lucas` 1976 critique (LUCAS, 1976), stating that conditions valid under given circumstances may no longer apply under others and, as a consequence, one cannot predict the effects of economic policies entirely upon relationships observed in the past.

An alternative approach is to use Engel curves, described by LEWBEL (2006) below (p. 1):

"An Engel curve describes how a consumer's purchases of a good like food varies as the consumer's total resources such as income or total expenditures vary"

Of course they also depend on other variables, both demographic (household size and structure, age, gender, race, educational level, location and labour market status, etc.) and non-demographic (e.g. prices, seasonal effects) (DAI *et al.*, 2012; LEWBEL, 2006). Applying Engel curves are not exempt of Lucas` critique – long-run scenarios implicate unprecedented levels of income, urbanization, technology, etc. – but they overcome the issues above discussed, even if inaccurately.

3.8 Informality and labour

This section explores briefly the representation of labour markets and informality in CGE modelling. These two aspects are out of the scope of the simulation performed in this thesis, but are worthy of debate, given their intrinsic relation to income generation and consumption. At a glance, we discuss the reason why modelling labour markets at a 'first-best' approach is far from adequate. SCHERS (2018) discusses the first-best versus second-best dichotomy (p. 70):

> *"First-best economies can be viewed as the assumption that economic agents have perfect foresight and that prices are set as such to maximise profits or optimise utility, and warrant that in any market supply equals demand. Second-best economies imply that expectations and/or information are imperfect, or that there are other reasons (like transaction costs, contract restrictions, or uncertainty and risk avoidance, e.g. prisoner's dilemma or the problem of free-riding) which cause mismatches in supply and demand of factors, inputs, consumption goods, etcetera. Assuming the world as a perpetual cycle of second-best economic conditions seems to be more realistic than assuming that natural laws and universal wisdom together with profit and utility maximisation will automatically drive all markets to perfect equilibria in the long run. Furthermore, perfect market equilibria do not imply perfect markets, in the sense that there might be socially undesirable consequences, such as poverty and pollution."*

Applied to labour markets, a simple (first-best approach) market clearing rule would see an economy`s wage level roughly as the output of labour supply and demand interaction. Firms would see it as the cost of the labour factor, whereas households would contrast the remuneration level to the utility brought about by leisure (that is, not working). Increasing the level of complexity, it could encompass inter-temporal decisions on utility (for households) and profits (for firms).

It is nevertheless broadly accepted that firms may pay wages above the market-clearing level. By doing so, they enhance workers welfare (and motivation) and thus productivity. Consequently, they prevent high evasion rates and training costs. This is known as the 'efficiency wages theory' (see FIELDS (2005)).

This would be one of the aspects that help explaining the existence of (involuntary) unemployment, but, more importantly, it makes a strong case for imperfect conditions to be taken into account when modelling labour markets. Presented next are a few other aspects concerning this question, as well as their representation in CGE modelling. We emphasize the issues we mean to implement during future model developments.

3.8.1 Labour supply

Treating labour supply at a more disaggregated level introduces market rigidities in the model. It is underlying for identifying the impacts of climate or trade liberalization policies on labour demand and the wage levels, intrinsically related to income distribution.

The formulation should balance between representing heterogeneity and allowing for some degree of mobility, especially in long-term analyses. For instance, BOETERS AND SAVARD (2011) shed a light on using different skill classes (according to educational level), the most common approach (p. 21):

> *"Conceptually, it is easy to extend the skill split to more than two classes. However, the more skill classes, the more challenging labour demand estimation, which becomes more likely to produce implausible substitution patterns (...). In addition, the more skill classes, the less plausible the implicit claim that skill is an unchangeable attribute of the households (i.e. that individuals cannot switch from one skill class to another)."*

Alternatives for representing labour supply include (BOETERS; SAVARD, 2011):

- Type of occupation (e.g. executive, mid-level technicians, farmers): this might be a more realistic approach in the sense that switching from one occupation to another may be more difficult than switching from low-skilled to high-skilled tasks within the same occupation;

- Sectoral employment. Analogous to the previous option, this approach considers that workers cannot shift from one sector into another (in the short-run), and sector have their own wage levels. This can extend to urban vs. rural classification.

- Income types (non-labour income): this approach relates the willingness of workers to supply labour based on the existence of other sources of income, such as pensions, social security benefits and rents.

Other options are also available and, in general, all of them assume the labour supply of each representative group to be fixed. Micro-simulation models described in section 3.4.2 are an alternative to this issue.

3.8.2 Labour demand

The challenge of representing labour demand in CGE modelling emerges from the traditional configuration of production functions, that is, nested CES functions. The complementarity and substitutability of different types of labour, as well as capital-skill complementarity are to be considered. Production factors that are complementary should be grouped at a low level of the nesting, obviously with a low elasticity of substitution, whereas substitute factors should be placed at a higher level, with a higher elasticity of substitution (BOETERS; SAVARD, 2011). However, existing literature hardly provides applicable estimates, so the parameterization of elasticities can only come from an educated guess.

3.8.3 Formal and informal labour

According to FORTIN *et al.* (1997), distinguishing formal and informal labour markets is underlying in distributional analyses, given that a large share of the most vulnerable workers, the poorest, belong to the latter.

In many developing countries, the informal sector accounts for a major share of the economy, but informal activities are often hardly kept by official statistics. Data availability is the first obstacle a modeller may come across, but not the only one. Informal labour is generally defined as that without secure contracts, worker benefits or social protection, but where should self-employed workers be allocated is unclear.

In fact, one can expect formal and informal labour markets to have different productivity, wage and taxation levels. This translates into different market clearing rules: whereas in the informal sector equilibrium wages would be set close to a full employment level, in the formal sector rigidities are expected (therefore wage should be set above the market-clearing level) (BOETERS; SAVARD, 2011).

Furthermore, understanding the degree of mobility between the two sectors is not trivial. Informal labour varies across sectors, with agricultural sectors demanding significantly more than industrial ones, for example (seasonal aspects may play a role). On the labour supply side, locational issues (e.g. rural vs. urban), social security coverage and the implicit costs of job-seeking are determinant.

GUERARD *et al.* (2014) discuss how to introduce informality in the Imaclim-S framework for the South African national version. They focus on the calibration of National Accounts elements, such as Value Added taxes and commercial margins.

4 The Imaclim-S Brazil model – Methods and data calibration

This chapter starts with a brief description of the fundaments of the static version of the Imaclim model, followed by an overview of its national version for Brazil. Methodological stages undertaken in this thesis are then described. They include the preparation of macroeconomic data, including the reconciliation of household surveys and the input-output framework (sections 4.2.2 to 4.2.3.1) and aggregation choices (section 4.2.5.1). The complete model equations and notations can be found in Annex I.

4.1 The Imaclim-S model – a distinct CGE approach

This section is based on the consolidated literature describing the fundaments of the Imaclim-S model, namely GHERSI *et al.* (2009), COMBET *et al.* (2010), WILLS (2013), WILLS AND LEFÈVRE (2012) and LEFÈVRE (2016).

Imaclim-S is a static CGE model designed to assess medium- to long-term macroeconomic impacts of aggregate price - or quantity-based carbon policies, in an accounting framework where economic and physical flows (with a special focus on energy balances) are equilibrated.

The model is based on the standard neoclassical model in the main feature that its description of the consumers' and producers' trade-offs, and the underlying technical systems are specifically designed to facilitate calibration on bottom-up expertise in the energy field. A special treatment is given to guarantee technical realism to the simulations of even large departures from the reference equilibrium. Other significant features include (i) an aggregate treatment of the general technical change induced by the shifts in energy systems; Imaclim-S thus operates in an endogenous technical change framework; and (ii) a sub-optimal equilibrium on the labour market.

Imaclim-S calculations rely on the comparative-static analysis method: they provide insights that are valid under the assumption that the policy-induced transition from the reference equilibrium to its policy-constrained counterpart is completed, after a series of technical adjustments whose duration and scope are embedded in the elasticities of production and consumption retained. The transition process in itself is however not described, but implicitly supposed to be smooth enough to prevent, for instance, multiple equilibriums, hysteresis effects, etc. (GHERSI *et al.*, 2009).

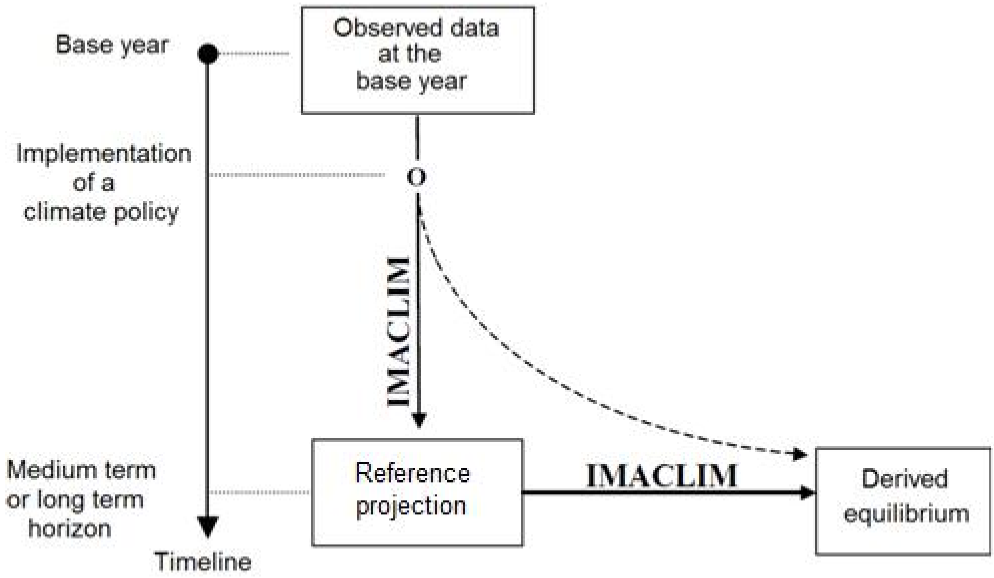
Imaclim-S is a ‘hybrid’ model in the sense that it pictures energy volumes that are not deduced from national accounts statistics and a single energy price assumption, but rather from an effort to harmonize these macroeconomic data with energy balances and energy prices statistics in the reference year. The hybridization of the input-output table facilitates the integration of some engineering expertise about technical flexibilities at a given time horizon. In particular, energy efficiency improvements of equipments and infrastructures used by both the producer and the consumer are bounded by exogenous asymptotes. As a result, the model exhibits price elasticities that gradually decrease as the relative energy prices increase, rather than constant elasticities (COMBET *et al.*, 2010).

The income flow associated with the flow of goods starts with the remuneration of production factors plus net payments from or to the rest of the world. It continues with distribution operations orchestrated by the public administration between institutional agents: taxes (payroll taxes, corporate tax, income tax, etc.) and transfers (unemployment benefits, social benefits, pensions, etc.). Once they have made their consumption and investment choices, agents lend or borrow on financial markets depending on whether their exhibit positive or negative savings. This affects their financial positions and the associated income flows (debt services, interest payments) (COMBET *et al.*, 2010).

4.1.1 Layout of the model

Imaclim-S operates by projecting the comparative static equilibrium of an economy (reference scenario), and then the deformation of this equilibrium where a climate policy (carbon constraint) is implemented (derived equilibrium or policy scenario).

Figure 4.1 - Imaclim-S layout



Source: GHERSI (2003)

The analysis of the impacts of a climate policy is therefore given in two stages:

1. Reference Scenario – The first step is the projection of the reference scenario which considers exogenous assumptions on GDP growth, demography and energy projections, for example. These exogenous premisses are embarked by the model and a new equilibrium, based on a hybrid input-output table is achieved. The projection is specifically designed to integrate data of the energy system calculated by any bottom-up model, ensuring consistency in both quantities and prices.

2. Policy Scenario – The derived equilibrium is a deformation of the reference scenario reflecting the climate policy applied. Expert information about behaviour of sectors under a carbon constraint (MAC curves, for example) is embarked on the model, and Imaclim-S equations relative to quantities and prices should be again satisfied under those conditions in order to calculate a new equilibrium.

4.1.2 Determinants of the macroeconomic impacts

The determinants of the macroeconomic impacts concerning the Imaclim-S model were described in a very synthetic way by COMBET *et al.* (2010). The comparative static analysis amounts to 'distort the image' of the no-policy economy by a given external shock. The particularities of such a distortion are induced by the interaction of sets of assumptions defining:

- The adaptation of the productive system, through the adjustment of inputs (labour, capital, intermediate consumption) to the variation of their relative prices, the evolution of total factor productivity (an endogenous technical progress coefficient is correlated to cumulate investment), and the influence of static decreasing returns.

- The rigidity of the labour market, formalized by a wage curve that describes a negative correlation between unemployment and the average net wage (BLANCHFLOWER; OSWALD, 2005).

- The impact on international trade: absolute exports and the relative contribution of imports to resources are elastic to terms of trade that evolve according to the cost of domestic production, facing constant international prices (the international composite good is the *numéraire* of the model).

- Public budget constraints: the ratio of public expenditures to GDP is assumed constant; social transfers (per capita unemployment benefits, pensions, and other transfers) are indexed on the average net wage.

According to COMBET *et al.* (2010), assuming constant savings rates and the adjustment of fixed capital formation on the demand addressed to the production system, the model is 'closed' by computing the capital flows that balance current accounts. Equilibrium is determined by the simultaneous adjustment of the volumes traded with the rest of the world, the domestic prices, the level of activity and interest rates.

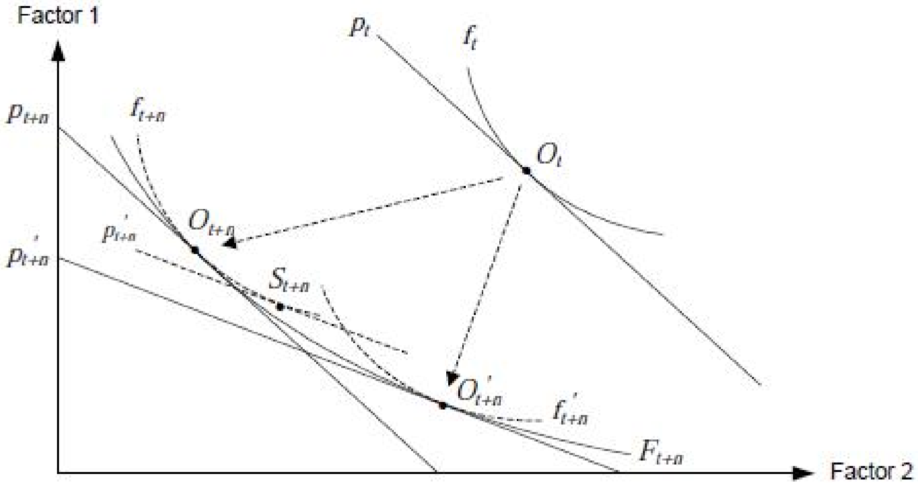
4.1.3 Induced Technical Change as a Dynamic Production Frontier

In order to assess the impacts of restrictive emissions mitigation targets, it is necessary to depict the economy explicitly in prices and physical quantities, presciding from functional forms with constant coefficients that ignore the reference departure level. Indeed, it is unlikely that the elasticity of substitution between capital, labour and energy at a \$10/t$CO2_e$ carbon price remains valid at a \$500/t$CO2_e$ carbon price. This is true for any specific industry, but also in aggregate production and demand functions because structural transformations of the economy induced by energy policies at some fixed horizon also become difficult when substitution possibilities vanish on both the demand and supply side. As HICKS (1963 in WILLS, 2013) puts it:

> *"A change in the relative prices of the factors of production is itself a spur to invention and to inventions of a particular kind—directed at economizing the use of a factor which has become relatively expensive"*

The figure below, adapted from RUTTAN (2002 in WILLS, 2013), illustrates this point: it pictures production techniques as combinations of two factors along unitary isoquants. The isoquant *ft* describes the available set of factor combinations at time *t*, from which the relative prices *pt* imply selecting *Ot*. At time *t+n*, assuming some technical change and constant relative prices *pt+n* = *pt*, the optimal factor combination will have shifted from *Ot* to *Ot+n*, on a new *ft+n* isoquant. Now, if the historical sequence of relative prices leads to *p ' t+n* instead, the economy should generate *f ' t+n* rather than *ft+n*, and the new optimum would be *O' t+n*. Exploring from date *t* the range of possible *t+n* relative prices reveals what AHMAD (1966) called an "innovation-possibility curve", i.e. an envelope *Ft+n* of the possible production functions *ft+n*. At *t+n*, along a given envelope the functions *f* mutually exclude one another: if the reference scenario leads to *ft+n*, an instantaneous shock in relative prices will shift the choice of technique to *St+n* rather than *O ' t+n*, since *f ' t+n* is no longer an available option.

Figure 4.2 - Induced technical progress



Source: RUTTAN (2002 in WILLS, 2013)

4.2 The Imaclim-S BR model

This section provides a detailed description of the Brazilian version of Imaclim-S model, first developed by WILLS AND LEFÈVRE (2012) and WILLS (2013), which subsidize this section.

The current version of the model includes the following features:

- Up to nineteen productive sectors: six energy sectors (biomass, coal, oil, natural gas, oil products, electricity), construction, freight and passenger transportation, livestock, rest of agriculture, six industrial sectors (paper, cement, steel, non-ferrous, chemicals, mining), rest of industry and a 'composite' sector (the rest of the economy – services mainly). Sectors can be aggregated according to simulation purposes;

- Extensions of benchmark hybrid I-O table[22]: emissions-intensive sectors are represented in physical units - tons of oil equivalent units for energy goods, tons

[22] Sectors with relatively homogenous products can be easily translated into physical units (e.g. ton of oil

for industrial goods, ton.km for freight transportation and pass.km for passenger transportation;

- Four institutional sectors: households, government, firms and the rest of the world. The household sector can be split according to the level of income and labour can be split according to the level of skill and whether it belongs to the formal or informal market. They can be aggregated according to simulation purposes.

4.2.1 Imaclim-S BR database

This section is based on WILLS AND LEFÈVRE (2012), WILLS (2013) and LEFÈVRE (2016), GROTTERA (2013) and GROTTERA *et al.* (2015), describing the fundaments and the work performed to build the hybrid Social Accounting Matrix, the main input to Imaclim-S BR.

4.2.1.1 Social Accounting Matrices (SAM)

The foundations of Social Accounting Matrices back from STONE AND BROWN (1962), further explored by PYATT AND THORBECKE (1976) and PYATT AND ROUND (1979). According to THORBECKE (2000, p. 1):

> *"The SAM is a comprehensive, disaggregated, consistent and complete data system that captures the interdependence that exists within a socioeconomic system. Alternatively the SAM can be used as a conceptual framework to explore*

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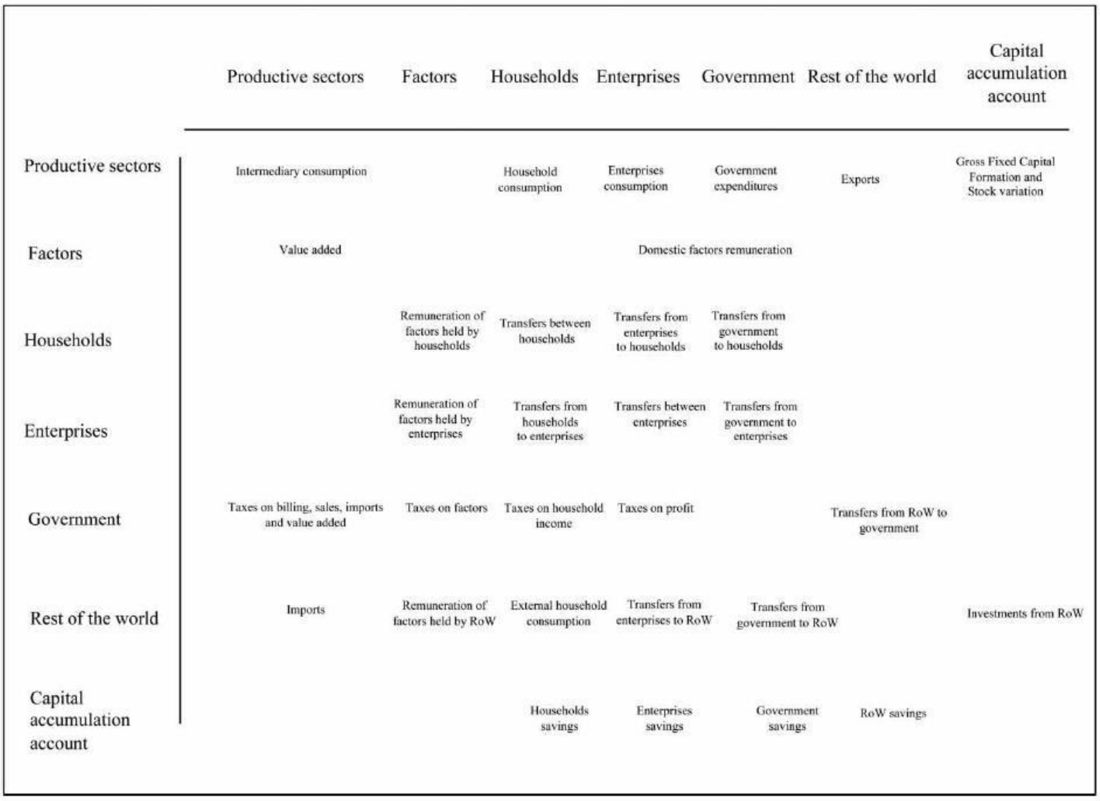
equivalent for energy sectors). For other sectors with miscellaneous production, however, this is not feasible. In this case, they are expressed in monetary values, controlled for price variations. This means that monetary units can actually be perceived as 'quasi-quantities', or rather as a volume index of production. One limitation is that this approach does not account of variations in the product mix of such heterogeneous sectors. When it comes to household consumption, it supposes the quality of products does not change.

> *the impact of exogenous changes in such variables as exports, certain categories of government expenditures, and investment on the whole interdependent socioeconomic system, e.g. the resulting structure of production, factorial and household income distributions. As such the SAM becomes the basis for simple multiplier analysis and the building and calibration of a variety of applied general equilibrium models. The chosen taxonomy and the level of disaggregation depend critically on the questions that the SAM methodologies are expected to answer. If the SAM is to be used to explore issues related to income distribution then the household account is to be broken down into a number of relatively homogeneous household groups reflecting the socioeconomic characteristics of the country or region under consideration. On the other hand, if the purpose of the SAM is to analyse intersectoral linkages, then a relatively detailed sectoral disaggregation of production activities using such criteria as characteristics of the good or service produced and type of technology employed in production is called for."*

The SAM can be seen as an extension of the input-output matrix, since apart from the product and resource markets, it helps delineating the characteristics of the labour force, government policies such as taxation and welfare transfers, and other allocations of income. In short, by incorporating SAMs into the supply and use framework, we can develop an extended input–output model that can be employed for analysing social and economic policy in a more comprehensive way (MILLER; BLAIR, 2009). Figure 4.3 depicts a stylized SAM, in which flows move from columns to rows.

Figure 4.3 - Stylized Social Accounting Matrix



Source: GROTTERA *et al.* (2015)

Imaclim-S BR uses a hybrid SAM, that is, productive sectors are depicted in physical quantities instead of monetary values. It is crucial to explore and understand the role and relative importance of material flows in the economy and the distribution of value added among sectors. The hybrid SAM brings a precise and mastered picture of the economy at base year conditioning the future energy-environment policy assessment (WILLS; LEFÈVRE, 2012).

4.2.1.2 National Account System data

The initial step to build the SAM is reconciliation of two different datasets that compose the Brazilian National Accounting System for 2005 and are provided by IBGE:

- MIP (*'Matriz Insumo-Produto'*): the input-output table balances the uses and resources of goods and services. The columns detail the cost structures of goods with input consumptions (V) and value added (VA) plus imports (M) and taxes. The rows discern intermediary consumptions for production (V) and final consumptions (household's consumptions (C), public administrations' consumptions (G), investments (I) and exports (X)). Its 110 products that belong to 56 sectors are aggregated into the model's 19 sectors in a square "product-product" framework, with no accumulation of stocks.

- CEI (*'Contas Econômicas Integradas'*): it complements MIP by detailing the primary and secondary distribution of income between six institutional sectors: financial firms, non-financial firms, households, non-profit organizations, public administrations and "rest of the world". The CEI is aggregated into four institutional sectors (households, firms, public administrations and "rest of the world"), and its many entries are simplified into a set of transfers at a level of aggregation comparable to that of the MIP. Basically the primary distribution of income is composed of productive factor remuneration (labour, productive capital and land) and income from property (financial income). The secondary distribution of income is made of indirect taxes and social transfers.

While the primary income distribution is by far the most important determinant of incomes received by the various socioeconomic groups, a secondary income distribution may work through the family, village, or, more important, through the state in the form of transfers and subsidies and taxes (LEFÈVRE, 2016).

The incorporation of CEI ultimately allows extending the traditional framework of general equilibrium modelling to the distribution of national income between economic agents, the resulting changes in the financial positions of those agents, and the corresponding debt payments. MIP and CEI data are finally combined in a unique SAM framework.

4.2.2 The hybridization process

As LEFÈVRE (2016) points out, explicit physical quantities are poorly represented by the 'quasi-quantities' commonly obtained from the MIP through the normalization of output prices. This arises out of a variety of reasons, such as the inclusion of services beyond the sheer physical consumptions, the heterogeneity of products, biases from the statistical balancing methods, etc.

Therefore, a rigorous calibration of the model requires some accurate accounting of the physical quantities of energy consumed, expressed in a relevant unit (e.g. tons of oil equivalent). This is valid for all material flows of interest: industry, agriculture and livestock and transportation.

Figure 4.4 illustrates the hybridization process performed by WILLS AND LEFÈVRE (2012). It departs from rearranging the National Energy Balance (BEN[23]), which gathers energy flows (in ktoe) for energy transformation and final consumption, in an I-O format like National Accounts with intermediary consumptions for productive sectors (IC) (within energy system and other productive sectors) and final consumptions (FC). This is done for the six energy sectors that compose the 2005 MIP.

An analogous proceeding is performed with data on flows of industrial products and livestock products expressed in ktons, and transportation expressed in t.km and pass.km, originating matrix Q.

The collection of end-use specific prices is another requirement: a second matrix (P) is composed by the identified price paid by different agents for each type of good, dismissing the single-price assumption. The data on price that were used to estimate the energy and material expenditures come from varied sources including National Energy Balance and ANP[24].

The development of physical balances and agent-specific prices matrices constitute Step 1 in Figure 4.4. The term-by-term product of Q and P (Step 2) defines the Energy Bill (V), a matrix of energy consumptions in monetary terms, which does not match that embedded in the MIP for physical products.

Since there is no energy embedded in those "surpluses", the remaining values must be redesignated to some non-energy sector, in this case the 'Rest of the Economy' sector (or `Composite`). This is Step 3.

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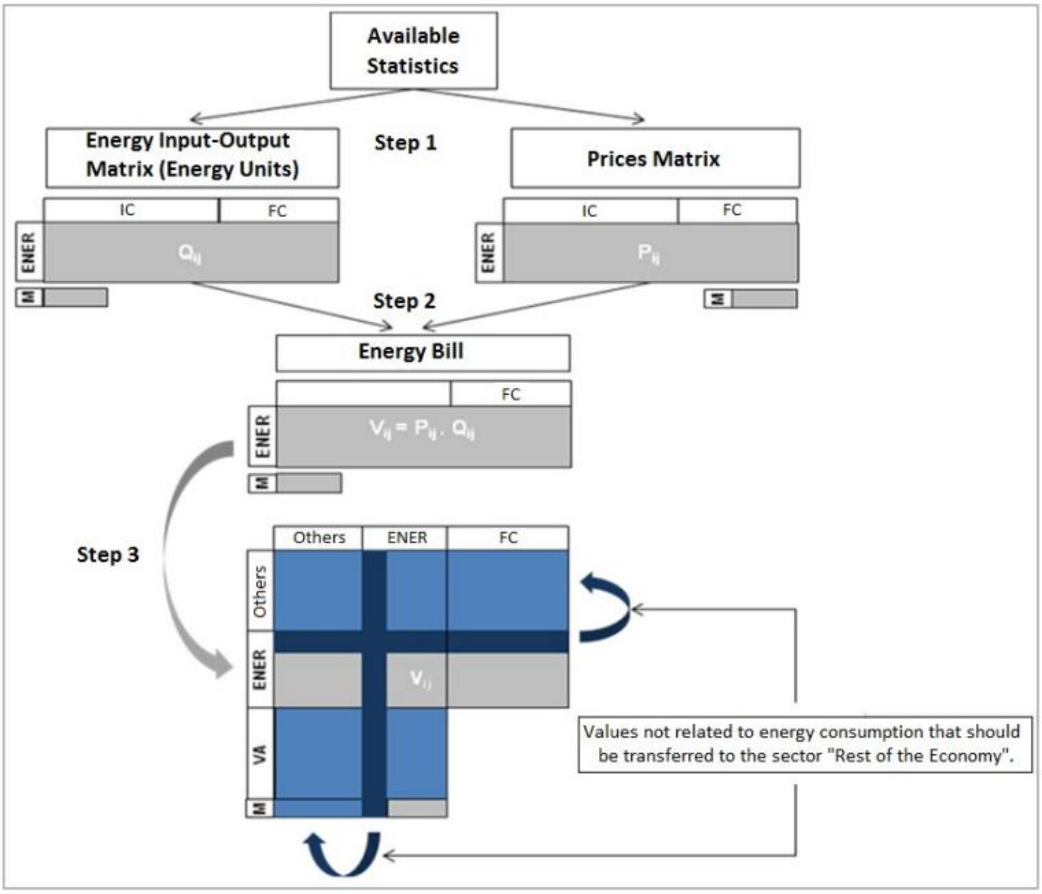
[23] Acronym for 'Balanço Energético National'.

[24] Acronym for 'Agência Nacional de Petróleo'.

Figure 4.4 - The hybridization process for Imaclim-S BR SAM



Source: LEFÈVRE (2012)

This comparison encourages to assign the gaps in monetary value revealed to composite goods out of material cycles well identified and isolated, meanwhile keeping the global size of the economy. It requires in particular commodity balances and statistics on prices.

The calibration of the model on this hybrid MIP (which is included in the final benchmark SAM) eventually leads it to depict (i) volumes of the non-energy goods that are traditionally derived from the single-(normalized)-price assumption, and (ii) volumes and prices of the energy goods that are strictly aligned on the available statistics. The differences in price of the same energy good from one agent to the other (e.g. the variable average prices of a kWh of electricity) are accounted for by calibrating "specific margins" to the different uses (LEFÈVRE, 2016).

4.2.3 Expenditures and income disaggregation and the characterization of labour force according to workers` profiles

One of the core objectives of the exercises performed using Imaclim-S BR is to understand how climate policies impact different social strata, namely regarding income and consumption possibilities. In order to do so, we sought to identify the varying expenditure and income formation profiles among ten percentiles of income for the totality of the Brazilian household sector.

In addition, we also sought to detail the workforce, by identifying the productive sector, level of labour qualification and whether the worker belongs to the formal or informal sector. This is important because climate policies affect productive sectors differently (depending on their level of carbon-intensity), and each sector deploys different types of workers relative to their skills and formality. Since wages are the households` main source of income (specially for poorer households), sectoral growth and variations in job creation as the aftermath of specific mitigation policies may play a major role in the distributive effects of climate action. These are the major contributions of this work in terms of the Imaclim-S BR database refinement and the simulation possibilities they accrue.

The outlining of households and workforce must be incorporated during the SAM construction process. Two main surveys carried out by IBGE are used to delineate expenditure, income, skill level and other relevant information on Brazilian households:

- The Consumer Expenditure Survey (POF[25]) provides information about the composition of household budgets, through the research of consumer habits, allocation of expenditures and distribution of income, according to characteristics of households and persons. The POF also investigated the self-perception of life conditions by the Brazilian population (IBGE, 2003).

[25] Acronym for ‘Pesquisa de Orçamentos Familiares’.

- The National Household Sample Survey (PNAD[26]) investigates, every year, and on an ongoing basis, general characteristics of the population, concerning education, labour, income and housing, besides others, at variable frequency, according to type of information needed by the country, such as characteristics of migration, fertility, nuptiality, health and food security, among other topics. Along 48 years, these statistics constitute an important tool for the formulation, validation and evaluation of policies aimed at the socioeconomic development and improvement of living conditions in Brazil (IBGE, 2005).

Microdata from surveys were processed in Stata, using Data Zoom, developed by the Department of Economics at PUC-Rio, which provides free-access codes for assessing IBGE microdata.

4.2.3.1 Income and expenditures calibration

The disaggregation of households in Imaclim-S BR is performed through the 'Representative Household Groups (RHGs)' approach (see section 3.4.1). This technique suits well the research purposes of this thesis, for it captures the impacts of climate policy for different households types, including their interactions with macroeconomic outputs (BOURGUIGNON *et al.*, 2008).

Microdata from National Household Budget Survey 2002-2003 (POF) (IBGE, 2003) relative to consumption of goods and services, other expenditures and sources of income was reconciled with the households` components of the 2005 base-year Social Accounting Matrix (SAM), disaggregating households in ten income deciles. This allows for understanding how different monetary and physical flows are allocated among classes and conceiving how their behaviour shall evolve in long-run scenarios. Annex II details the reconciliation among Imaclim-S BR sectors and POF categories.

[26] Acronym for 'Pesquisa Nacional por Amostra de Domicílios'.

The survey provides information regarding the household profile (members' age, total income, expenditure levels for several categories), which we use to build our datasets. The chosen criteria for ordinating income deciles uses total household income weighted by consumption units, applying the OECD modified scale (described in section 3.6). The selection assigns the following value for households members:

- Head of household: 1
- Other adults: 0.5 (each)
- Children under age 14: 0.3 (each)

Household h considered income is R_{uc}:

$$Ruc_h = R_h \big/ (1 + 0.5 * (p_{ah} - 1) + 0.3 * (p_{ch}))$$

in which R_h is the total income of household h, and p_{ah} is the number of adults in household k and p_{ch} is the number of children in household h.

The aggregation of observed household provides the representative households relative to each decile. It is worthy to mention that POF also supplies the assigned weight of each household in the dataset, which is key to carrying out estimates.

The procedure follows by calculating the share of the representative decile for SAM components, using the same formulation as in GROTTERA *et al.* (2015)[27]:

$$\mu_{hi} = (Q_{hi} F_h) / \sum_{h=1}^{10} (Q_{hi} F_h)$$

where:

μ_{hi} represents the share of decile h in total expenditure (for consumption) or payment (for income) for item i

Q_{hi} represents total expenditure or payment of decile h for item i

[27] In GROTTERA *et al.* (2015), the number of households per income class varies, for they are defined by minimum wage ranges.

F_h represents total households in decile *h* (approximately equal in all deciles)

Adjusting the weights found in household surveys into the macroeconomic database is the most adequate approach to deal with possible inconsistencies between sources, as indicated by ROBILLIARD AND ROBINSON (2003) (see section 3.5). This approach is especially necessary regarding data from POF, for which the base year, 2003, differs from the one in the SAM[28].

Savings account work as a closure device, that is, they assure the balance for the household sector. Total savings are provided by CEI, hence a simple pro-rata assessing the gap between total income and total expenditure for each decile is applied into the aggregate.

4.2.3.2 Household and labour calibration outputs

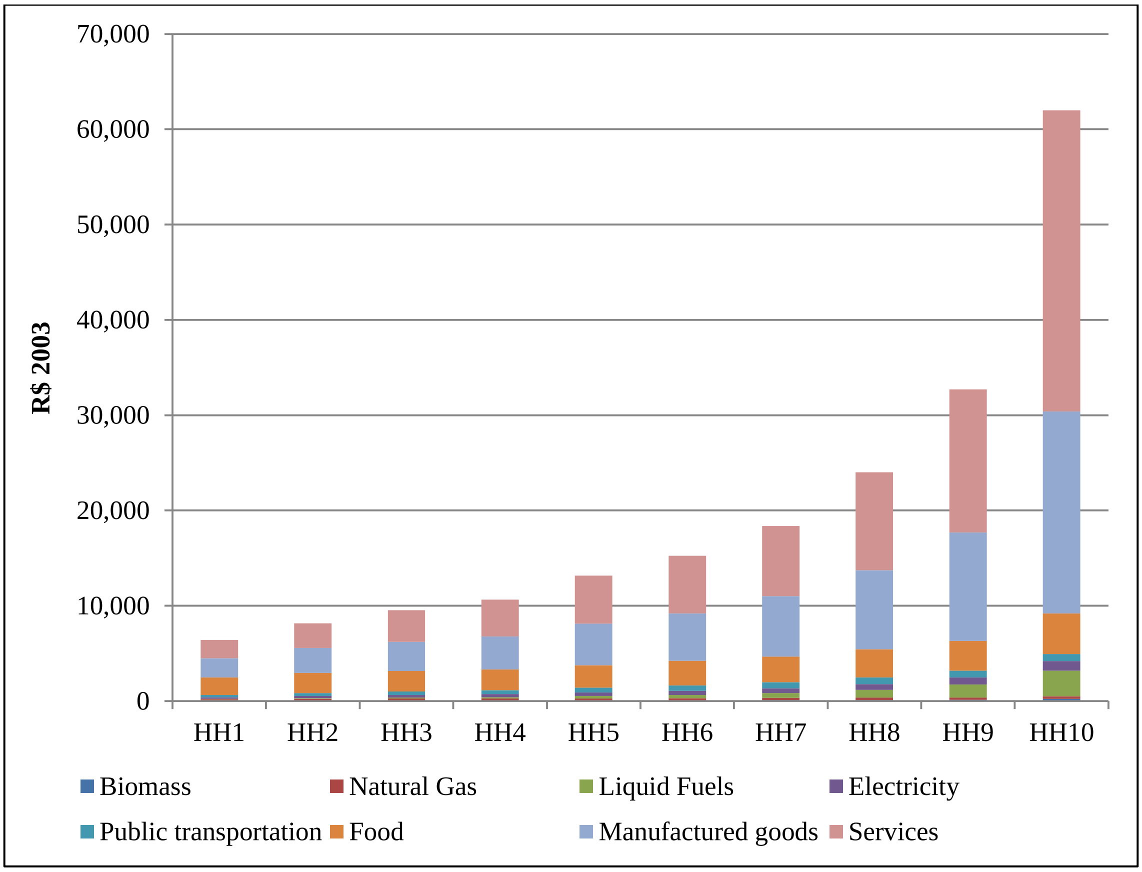
Figures below show the SAM components disaggregated by income deciles. We highlight that, according to the specific aim of each study, households classes can be aggregated differently in the CGE model.

Annual household expenditure for Imaclim-S BR categories is shown in Figure 4.5 (some categories were aggregated to make visualization easier). Durable goods and services account for the largest share of expenditures for all classes. Lower income deciles spend a significant share of their consumption budget on food, whereas top deciles do not. In fact, total expenditure on food does not vary as much as for goods and services, for example, a sign of saturation after basic needs are met (even though part of expenditures for food is comprised in services. Food out of the household – restaurants, cafés, etc. – is computed within this category. It is important to highlight that richer classes spend a much greater share of income in this type of service than lower income

[28] FERREIRA *et al.* (2008a) use PNAD data and highlight that the questionnaires still contain insufficient detail on capital incomes, production for own consumption, and incomes-in-kind. As a result, some evidence suggests that some of the incomes are underreported, particularly in rural areas—and this problem is more severe at both tails of the distribution. This is likely to be valid for POF too.

ones). Only top income classes have expressive expenditures with liquid fuels explained by higher car ownership rates. Analogously, their level of expenditures with electricity is also much higher, related to living space and appliance ownership. Electricity however accounts for a much larger budget share among bottom deciles than for top ones.

Figure 4.5 - Annual average household expenditure per category (R$ 2003)



Source: Author`s elaboration, using microdata from POF 2002-2003 (IBGE, 2003)

It is very interesting to compare the figures above with the results in ABREU *et al.* (2017), in which a similar analysis for household deciles` consumption is performed focusing on energy requirements (also using POF 2002-2003). The authors find that nearly 67% of total average household energy requirement comes from indirect energy, for example embedded in goods and services. From total indirect energy consumption, approximately 36% relates to transportation (public transportation and freight services), and 20% relates to food. An assessment at the decile level shows that the latter decreases with income whereas the former increases.

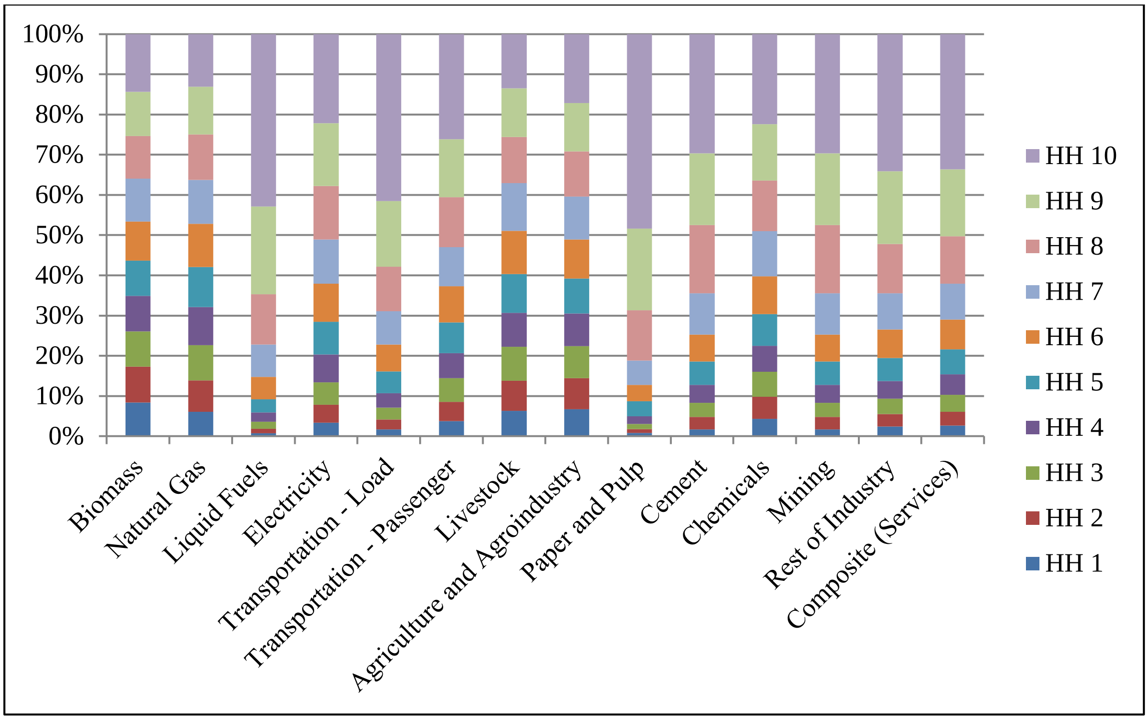
Comparing figures for the different income deciles, the authors find that total energy requirements (direct and indirect) in the richest and the poorest decile differed by a factor of 9. Regarding direct energy exclusively, the top decile demand four times more than the bottom one. In contrast, for indirect energy, the gap widens drastically: the richest decile`s requirements are 14 times higher than the poorest`s.

Figure 4.6 depicts the share of each household decile in final consumption categories. Given its level of total expenditures, the highest decile (HH10) dominates virtually all categories. Its share on liquid fuels demand is markedly high (43%), due to consumption of gasoline and diesel in private vehicles. For lower classes it is likely that liquid fuel consumption relates rather to Liquefied Petroleum Gas (LPG) for cooking than fuels for transportation – HH1 accounts for only 1% of total consumption. Analogously, biomass consumption probably refers to ethanol for private transportation among the top deciles, and to traditional biomass (fuel wood and charcoal) for lower ones.

Richer households also account for a high share of manufactured goods (Rest of Industy - appliances, private vehicles, clothing, furniture, etc.), and services. Concerning household demand, the chemicals sector comprises mainly cleaning and hygiene products, which explains the dominance of top classes[29] .

[29] Other industrial sectors are also dominated by top deciles, but their absolute levels are negligible compared to other categories.

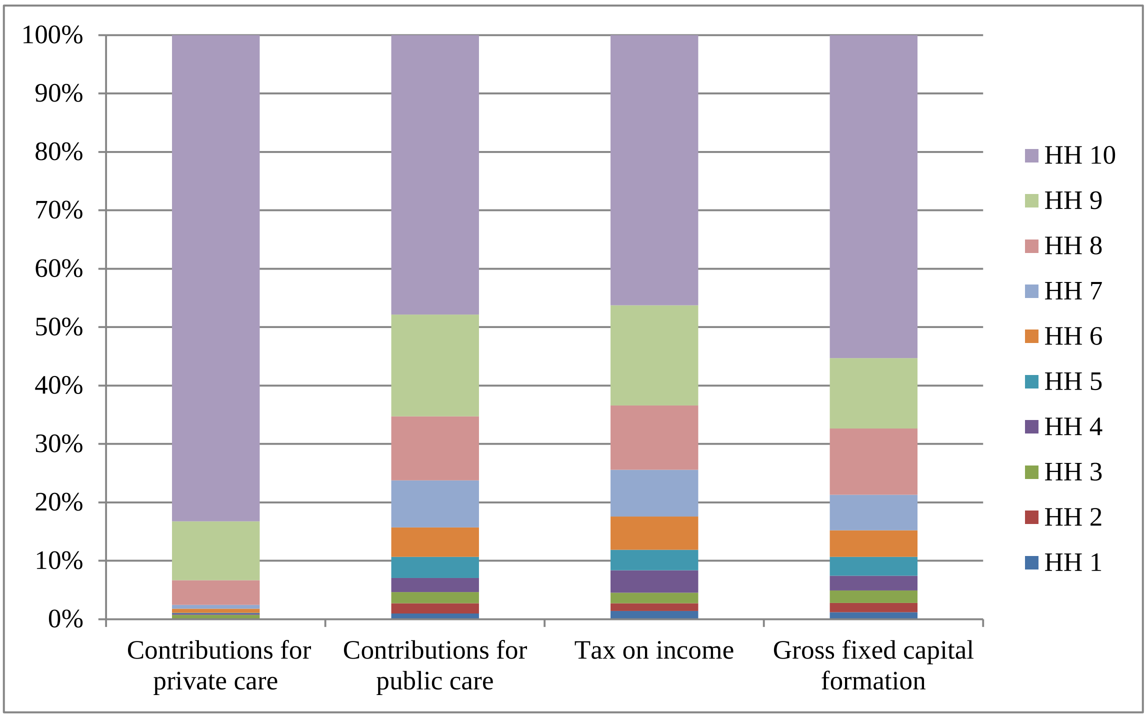
Figure 4.6 - Consumption expenditures disaggregation per income decile (%)



Source: Author`s elaboration, using microdata from POF 2002-2003 (IBGE, 2003)

For non-consumption expenditures (Figure 4.7), the dominance of top deciles is even stronger, namely contributions for private care (10% for HH9; 83% for HH10). Contributions for public care and relate to workers` employment situation (formal vs. informal) and to wage levels, hence top classes also dominate. The same is valid for taxes on income, which also depend on other sources of income rather than labour.

Figure 4.7 - Other expenses disaggregation per income decile (%)

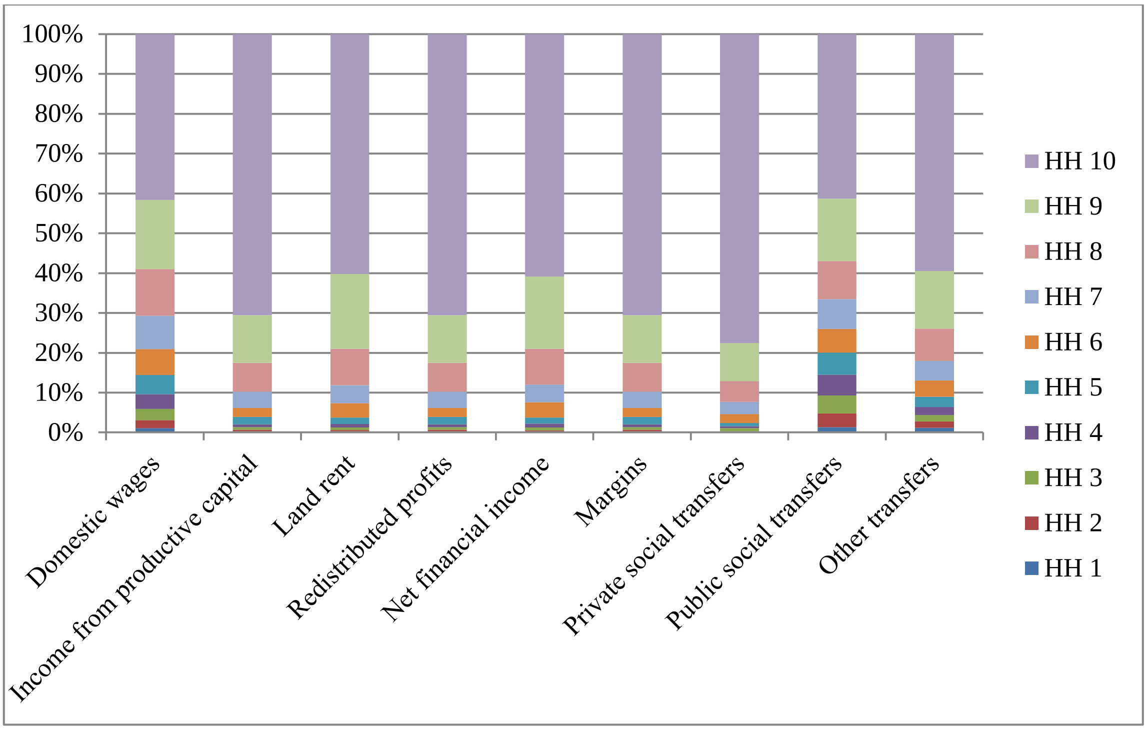


Source: Author`s elaboration, using microdata from POF 2002-2003 (IBGE, 2003)

Figure 4.8 splits income among households. The top decile (HH10) receives 42% of domestic wages, while only 1% is destined to HH1. A similar distribution is observed for public transfers, unveiling the huge disparities in governmental expenditures with pensions and retirements – usually destined to top classes – and other transfers such as the social cash transfers from *'Bolsa-Família'* destined to lower strata (even though this programme was still incipient in 2005).

Private social transfers are very unevenly distributed, with HH9 and HH10 accounting for 10% and 78% of total amount, respectively. Similar patterns are verified for all sorts of rents.

Figure 4.8 – Income sources disaggregation per income decile (%)



Source: Author`s elaboration, using microdata from POF 2002-2003 (IBGE, 2003)

4.2.3.3 Workforce profile

Microdata from the 2005 National Household Sample Survey (PNAD) (IBGE, 2005) was used to outline the labour sector according to household income levels, which are important components to be further applied to the Social Accounting Matrix items. Total years of study determine the level of the worker`s qualification (low, medium or high skill[30]); contribution to social security system is a dummy variable that determines if the worker belongs to the formal or informal sector; the productive sector to which the worker belongs was also identified. For each household, the head of the household was used as reference. Essentially, productive sectors remunerate the labour factor and it then allocates the labour income among household deciles, as shown in

[30] Years of formal education, according to workers´ level of skill

Up to 8 years: low-skilled

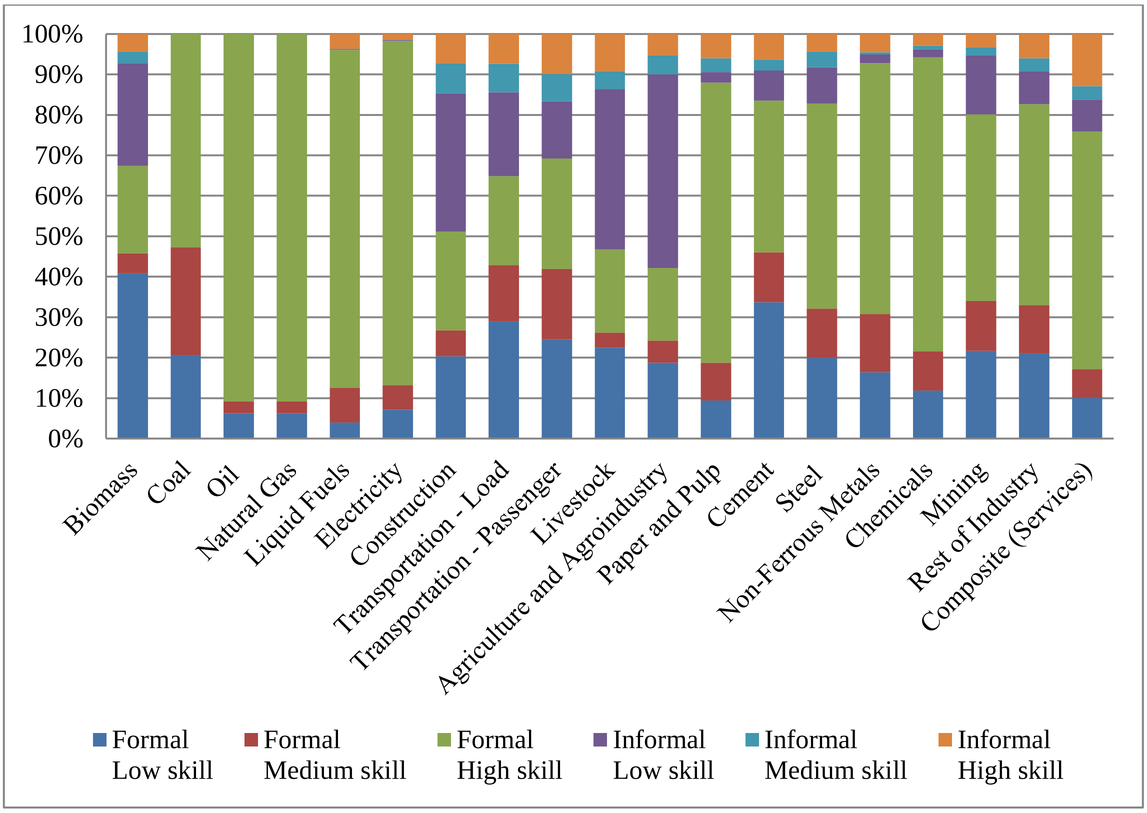
Between 9 and 11 years: medium-skilled

More than 11 years: high-skilled

Figure 4.9. As in the case of household income classes, the labour component can be aggregated in various ways depending on the focus of each model simulation.

Unsurprisingly, high-skilled workers in the formal market absorb the largest share of wages, especially in energy sectors (91% of oil wages; 85% of electricity). Informal labour in these sectors virtually inexists. The only exception lies in the biomass sector, which employed a fairly large share of unqualified workers, both formal and informal – a trend partially reversed due to recent mechanization efforts in sugar cane crops. The agriculture, livestock and construction sectors also deploy a many low-skilled workers, with high levels of informality.

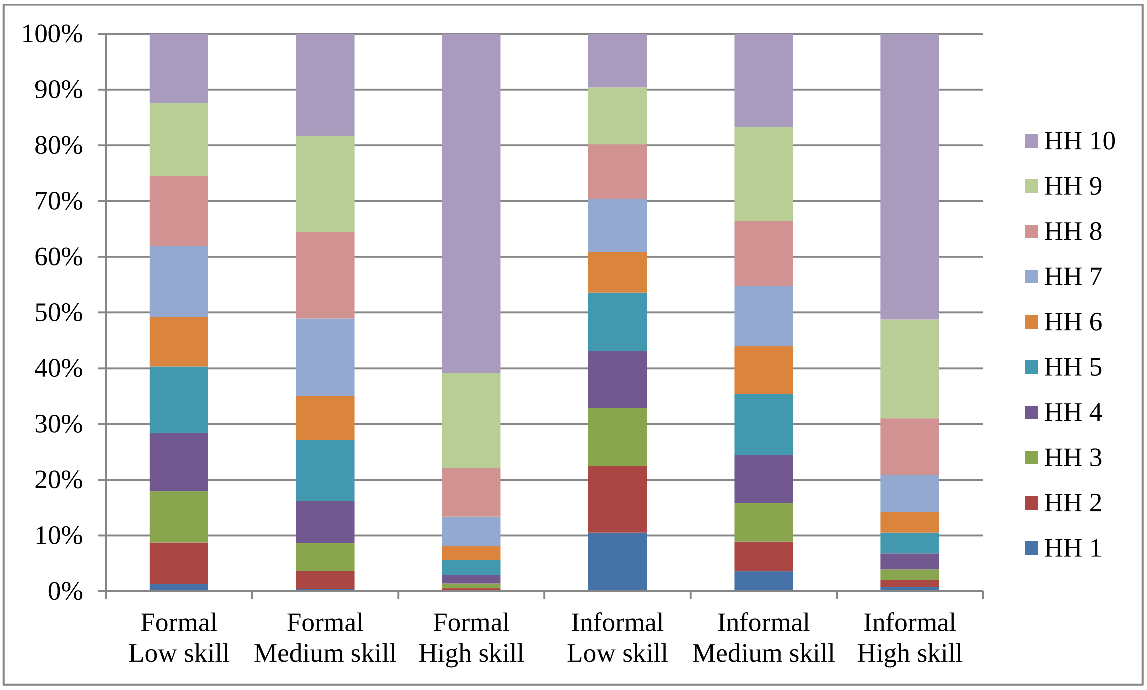
Figure 4.9 - Remuneration of labour income according to level of qualification and formality, per productive sector (%)



Source: Author`s elaboration, using microdata from PNAD 2005 (IBGE, 2005)

Educational levels and income are highly correlated (BAIOCCHI *et al.*, 2010; NERI, 2011), which is reflected in Figure 4.10. More than 60% of formal qualified labour wages are paid to households in decile HH10. In contrast, 10% of informal low-skilled labour wages – the lowest - are destined to households in the bottom decile.

Figure 4.10 - Remuneration of labour income according to level of qualification and formality, per income decile (%)



Source: Author`s elaboration, using microdata from PNAD 2005 (IBGE, 2005)

4.2.3.4 Main characteristics of households

Households` characteristics[31] are not explicitly translated to the SAM framework. It is nevertheless worthy to present them, given their explanatory power on consumption and income profiles (it also allows for acknowledging that they are in line with existing literature discussed in section 2.3).

The average household size is inversely proportional to income. The share of rural dwellings is larger within bottom classes; the same is valid for single-mother households. The share of households in which the head is between 18 and 24 years is

[31] Figures in Table 4.1 were calculated using microdata from the 2009 PNAD (IBGE, 2009), profiting from efforts undertaken during the ECOPA project.

higher in bottom deciles, evidencing different childbearing age profiles across classes. In contrast, households with a reference person above 65 years are more commonly observed within richer classes, reflecting the presence of retired people and the wealth accrued during life.

Table 4.1 - Household profile per income decile

	Total	HH1	HH2	HH3	HH4	HH5	HH6	HH7	HH8	HH9	HH10
Average members per household	**3.21**	3.50	3.39	3.34	3.25	3.21	3.13	3.13	3.06	3.05	3.08
Geographical classification											
Rural	**15%**	34%	25%	20%	17%	15%	12%	13%	8%	6%	5%
Urban	**85%**	66%	75%	80%	83%	85%	88%	87%	92%	94%	95%
Household type											
Couple without children	**18%**	7%	10%	11%	12%	19%	18%	23%	23%	25%	25%
Couple with children	**49%**	57%	61%	61%	38%	50%	51%	41%	46%	44%	42%
Single mother	**15%**	21%	20%	19%	13%	15%	14%	13%	14%	13%	11%
Other types of family	**19%**	15%	9%	10%	37%	16%	17%	23%	17%	18%	22%
Age of household reference person											
Less than 18 years	**0%**	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
18 to 24years	**4%**	8%	7%	6%	5%	4%	4%	4%	3%	2%	2%
25 to 45years	**44%**	59%	56%	55%	37%	44%	43%	35%	39%	38%	35%
46 to 65 years	**37%**	30%	29%	31%	33%	34%	37%	37%	42%	45%	46%
more than 65 years	**15%**	3%	8%	9%	25%	18%	15%	24%	17%	15%	17%
Housing status of occupation											
Owners	**69%**	69%	66%	66%	68%	68%	69%	71%	70%	71%	73%
Becoming owners	**4%**	2%	2%	3%	3%	4%	5%	5%	6%	7%	7%
Tenants	**17%**	13%	16%	18%	17%	18%	18%	17%	18%	18%	17%
Others	**10%**	16%	16%	13%	12%	10%	8%	8%	6%	4%	3%

Source: Author`s elaboration, using microdata from PNAD 2009 (IBGE, 2009)

4.2.4 Recent applications of the Brazilian version of Imaclim

Imaclim recent applications include policy-oriented and stakeholder-supported scenario exercises. In '*Implicações Econômicas e Sociais: Cenários de Mitigação de GEE 2030*'[32], LA ROVERE *et al.* (2016) build three sets of scenarios up to 2030 through a participatory process, composed of experts from the government, private sector, academia and civil society. Economic and social impacts are tested for (a) a Government Plan Scenario (GPS), including measures foreseen in the National Climate Change Plan[33]; (b) Additional Mitigation Scenario 1 (AM1), the expansion of measures considered in GPS, plus additional measures; (c) Additional Mitigation Scenario 2 (AM2), early implementation or expansion of measures from AM1, plus additional measures[34].

'Pathways to Deep Decarbonization in Brazil' (LA ROVERE *et al.*, 2015) is innovative in two senses: it is the first analysis carried out with the model for a long-run horizon up to 2050 and it does so using a backcasting approach to identify the required action to reach safe GHG concentration levels. It follows the IES Brasil 2030 AM2 scenario with a carbon tax up to 2030. From 2031 up to 2050, ambition increases even further, as well as the carbon tax, which reaches 150 US$ per tCO_2e in final year.

LEFÈVRE *et al.* (2018) explore the articulation between climate and oil policies in the medium-run in Brazil, discussing the possibilities for exploiting pre-salt reserves, their impacts on economic performance and ultimately alerting for the risks of 'Dutch Disease'.

In '*Emissão de Gases de Efeito Estufa – 2050: Implicações Econômicas e Sociais do Cenário de Plano Governamental*', WILLS (2017 in LA ROVERE et al.

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[32] Henceforth referred to as 'IES Brasil 2030'.

[33] See BRASIL (2009).

[34] Additional Mitigation scenarios include the implementation of measures solely through regulatory instruments and command-and-control mechanisms or by imposing a global carbon tax on burning fossil fuels (starting in 2015 and growing linearly up to US$20 and US$100 per tCO_2e in 2030 for AM1 and AM2, respectively).

(2017)) use the more recent version of the Brazilian Imaclim, which includes recursive features allowing to better represent the economic and technical pathway behind a long-term transition. Intermediate equilibria (including feedback dynamics) allow for simulating different growth regimes, investment requirements and carbon tax levels[35]. It is also worthy to mention that this scenario serves as the basis for the reference projection simulated in this thesis. Additionally it works as the basis for assessing total GHG emissions, including non-energy related emissions. This will be explained in detail in section 4.2.5.2.

4.2.5 Specificities to this version: parameters and aggregation choice, total GHG emissions assessment

Presented next are particular model features and choices required to conduct this research`s specific objectives. The numerical computation software Scilab (SCILAB ENTERPRISES, 2012) is used for performing simulations on IMACLIM-S BR.

4.2.5.1 The chosen aggregation of Social Accounting Matrix components

Productive sectors, originally nineteen, were aggregated in twelve. The final sectors were also reconciled with COICOP[36] categories, in a deeper level of detailing. This is underlying both to assess the evolution of specific categories in the reference scenario and to allow for lifestyles simulations in the alternative pathways. This documented in BARBIER *et al.* (2018) and will be further discussed in Chapter 5.

[35] Model improvements were conducted under the scope of the MILES project (Modelling and Informing Low Emission Strategies), from Institut du Développement Durable et des Relations Internationales (IDDRI).

[36] Acronym for “Classification of Individual Consumption According to Purpose” (UN, 2018)

Table 4.2 - Aggregation of Imaclim-S BR sectors

Aggregation	Original Imaclim-S BR sectors	COICOP categories
1. Biomass	Biomass	Ethanol Fuel wood Charcoal
2. Coal	Coal	n/a
3. Oil	Oil	n/a
4. Natural Gas	Natural Gas	Natural gas
5. Oil products	Oil products	Gasoline Liquefied Petroleum Gas (LPG)
6. Electricity	Electricity	Electricity
7. Public Transportation	Transportation - Load Transportation - Passenger	Road Rail Water Air
8. Livestock	Livestock	n/a
9. Agriculture and Agroindustry	Agriculture and Agroindustry	Bread & cereals Fruits & Vegetables Poultry Other meats Beef Fish & Seafood Animal products Oils and fats Beverages Other foods

10. Energy-intensive Industry	Paper Cement Steel Non-ferrous metals Chemicals Mining	Goods for household maintenance Hygiene items
11. Rest of Industry	Construction Rest of Industry	Household appliances Furniture and furnishing Clothing, footwear, personal effects Purchase of individual vehicle Telephone, audiovisual, computer Audiovisual and information processing equipment Other recreational items and equipment
12. Services	Composite (Services)	Feeding out of home Actual rentals for housing Loan payments for dwelling Water supply and miscellaneous services relating to the dwelling Services for household maintenance Personal care services Individual vehicle maintenance and others services Health services Private health care School fees for primary or secondary education Telephone and postal services Sports and culture (services) Other expenses

Source: Author`s elaboration

In the household sector, middle income deciles of representative households were also treated aggregately. In general, the poorer the household, the bigger its size. Hence, lower income deciles account for a higher share of total population than top ones. Households are organized as follows:

Table 4.3 - Aggregation of Imaclim-S BR household sector per income decile

Aggregation	Original income deciles	Share of population in 2005
HH1	HH1 (10% poorest households)	12%
HH2	HH2 HH3	22%
HH3	HH4 HH5	20%
HH4	HH6 HH7	19%
HH5	HH8 HH9	18%
HH6	HH10 (10% richest households)	9%

Source: Author`s elaboration

One single type of labour was used in this exercise, aggregating all six types of working skill types into one (Table 4.4). Efforts undertaken with microdata treatment to calibrate income and consumption enabled to outline the profile of the workforce as well. These are fairly time-consuming tasks, but synergies between the two themes are undeniable; data is supplied by the same household surveys. However, considering the coverage and depth of this exercise, labour dynamics is beyond the scope of our effort, albeit the undoubted interplay between labour markets, income and consumption. Further model developments are still needed in order to represent them as comprehensively as the complexity level demands. They are discussed in section 6.6.2.

Table 4.4 - Aggregation of Imaclim-S BR labour factor

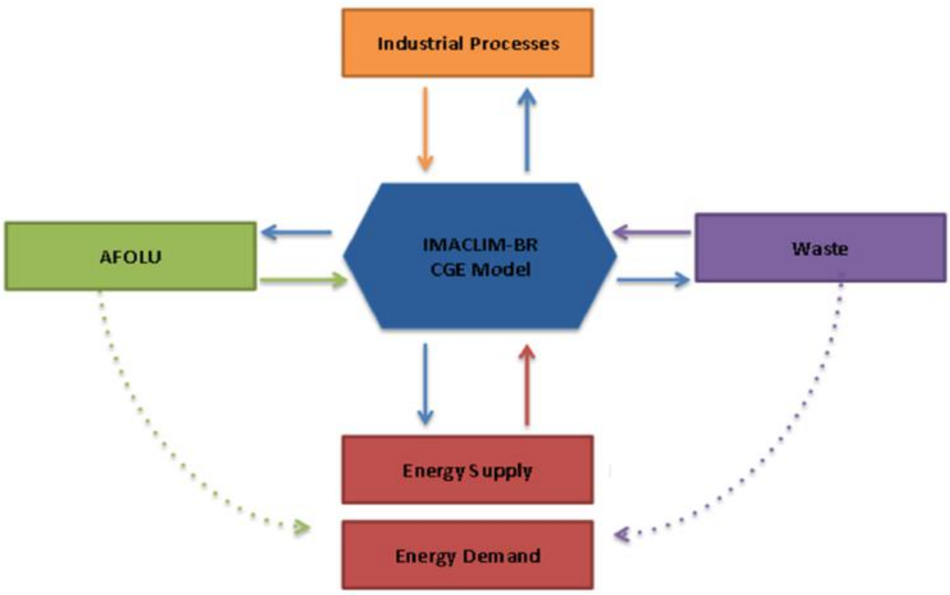
Aggregation	Original labour type levels
Labour	Formal; Low-skilled Formal; Medium-skilled Formal; High-skilled Informal; Low-skilled Informal; Medium-skilled Informal; High-skilled

Source: Author`s elaboration

4.2.5.2 Greenhouse gases final emissions assessment

Imaclim-S BR assesses exclusively emissions related to burning fossil fuels. Non-energy related emissions (from agricultural and livestock practices, land use, industrial processes and waste) must be estimated through a side-analysis, coupling bottom-up sectoral models that account for their specific emissions with Imaclim-S BR. Figure 4.11 depicts the integrated modelling framework, in which Imaclim-S BR is the core model, linked to BU tools.

Figure 4.11 - Modelling framework: integration of Imaclim-S BR and sectoral modules



Source: Adapted from WILLS (2013)

In this exercise, no bottom-up assessment was performed. However, an assessment of total GHG emissions is required in order to identify the mitigation potential of actions such as reduced meat consumption and waste generation. As mentioned in section 4.2.4, the Governmental Plan Scenario of (LA ROVERE *et al.*, 2017) is the basis for the reference scenario used in this thesis. Total GHG emissions were determined on a pro-rata basis, by comparing the Imaclim sectoral output results in the cited report with the model`s results for this exercise, in each scenario. Given that the core scenario assumptions and the economic productive structure are the same in the two exercises, this can be considered an adequate approach for estimating non-energy emissions levels. Detailed GHG emissions from IES_2050 scenario can be found in Annex II.

4.2.5.3 Choices of parameters and sensitivity analysis

The choice of model parameters is defined based on specific research purposes particular to this exercise. They are valid for all three simulated scenarios. In general, parameters selection is fairly conservative, and it is worthy to mention that they are also a means to achieve the desired representation of macroeconomic aggregates in the reference scenario. In other words, they are used to set up the reference scenario, attaining the anticipated levels of exports, imports, unemployment, sectoral output, among others that constitute the storylines (described in the next chapter).

In this thesis, no sensitivity analysis is conducted, focusing rather on the effects of household demand variations than in the model`s features themselves. Seminal work documenting Imaclim-S BR investigates in depth the model`s responsiveness to changing parameters. WILLS (2013) tests the impacts of varying terms of trade on GDP[37], as well as how both GDP and average wage behave when altering the wage

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[37] WILLS (2013) tests the effects on GDP when the elasticity of exports in relation to domestic prices, initially set at 1.5, varies between 0 and 3. He finds that above 0.75 levels, no significant variations in GDP occur.

curve flexibility (negotiation between workers and employers)[38]. LEFÈVRE (2016) also performs sensitivity analyses for these parameters, assessing the impacts on various indicators. The author also explores the impacts of different possibilities of representation of the wage curve, indexing unemployment levels either to real or nominal wages. Finally, the sensitivity of the results to the flexibility of technical systems, that is, higher possibilities of factor substitution, is also tested[39].

In addition, parameters are chosen based on existing literature and the model has been used to perform relevant scenarios exercises, described in the previous section (4.2.4). They have proven to be adequately calibrated to represent consistent energy-economy projections with Imaclim-S BR.

In this study, the wage curve is indexed to real wages at a low elasticity level set at -0.1[40]. Complementarily, selected labour-intensive sectors may replace labour and capital and vice-versa, according to production factors costs variations. Likewise in this case, the elasticity of substitution between productive factors is low (0.15). Elasticities of imports and exports, which respond to terms of trade, range between 1 and 1.7.

[38] The author tests the flexibility of workers´ bargain power variation, initially set at -0.05. The sensitivity analysis verifies that GDP increases and real wages drop the lower the parameter (ranging from 0 to -0.5) (WILLS, 2013).

[39] Other theses using national versions of Imaclim-S also explore such dynamics: LE TREUT (2017) for France and SCHERS (2018) for South Africa.

[40] Selected from BLANCHFLOWER AND OSWALD (2005).

5 Low carbon strategies in the Brazilian context - Scenarios storylines, drivers and assumptions

The initial part of this chapter introduces the Brazilian context and discusses the articulation of climate and socioeconomic goals, bearing in mind the country`s peculiar emissions profiles and development agenda. Future prospects for population, urbanization, economic structure, among others are explored. The implications on energy demand, household consumption and, ultimately, GHG emissions are drawn, setting the basis for quantifying the scenarios assumptions that are presented in the second part.

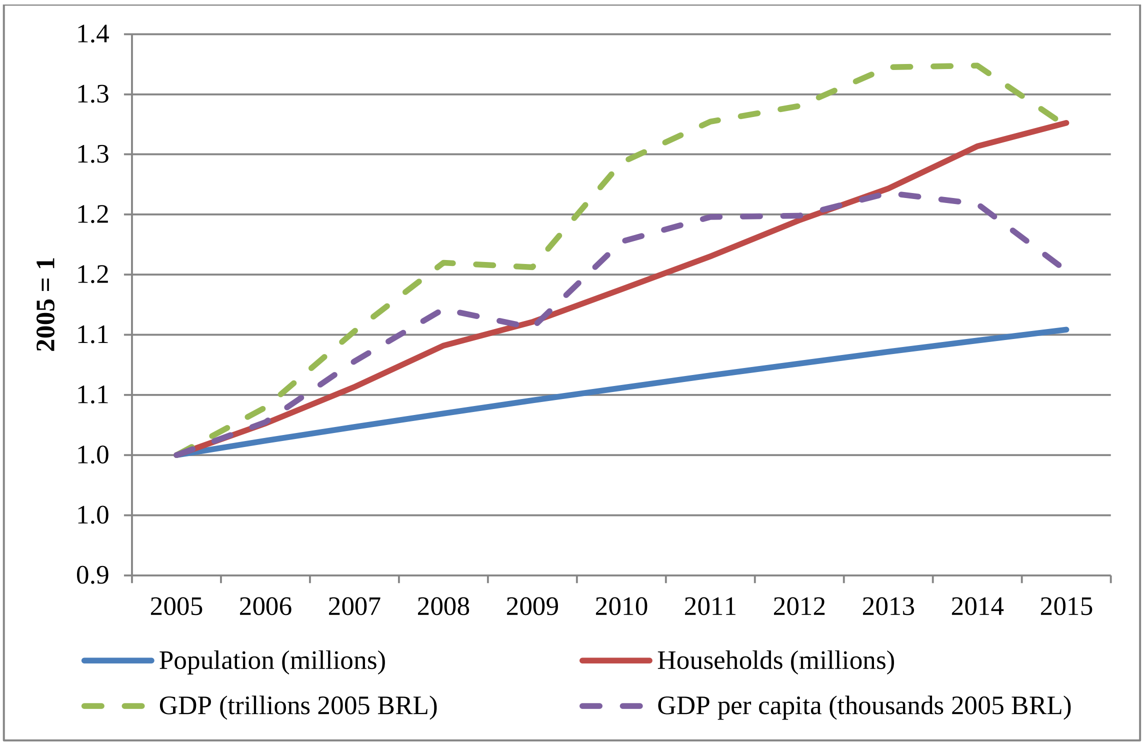
As discussed in section 3.1, scenarios exercises do not consist in forecasting a ‘most likely’ future outcome. Furthermore, they are not inherently normative, in the sense that they do not prescribe more or less desirable pathways. Scenarios are rather exploratory, they sign the resulting implications of a coherent set of assumptions.

5.1 Brazil in the context of a climate-constrained world

As many other developing countries, Brazil has made outstanding progress regarding its economic and social agendas during the last decades. Benefiting from favourable circumstances such as high international commodities prices and expanding workforce, the country managed to sustain economic growth while improving the population`s living conditions.

Domestic policies targeting economic soundness, such as primary surplus, inflation bands and floating exchange rates, enabled the conditions for enhancing the business environment and formal job creation. Figure 5.1 depicts the expansion of population and total households, as well as GDP and GDP per capita evolution between 2005 and 2015. Table 5.1 shows the main demographic trends during the same period, such as urbanization and decreasing household size. It also presents the Human Development Index evolution, which rates key dimensions of human development into a synthetic index (life expectancy, education, per capita income, among others).

Figure 5.1 - Population, households, GDP and GDP per capita evolution in Brazil from 2005 to 2015 (2005=1)



Source: IBGE (2013a, 2016, 2018)

Table 5.1 - Demographic and social indicators evolution in Brazil from 2005 to 2015

	2005	2010	2015	2005-2015 annual average variation (% p.y.)
Population (millions)	185.2	195.5	204.5	1.0%
Households (millions)	53.4	60.7	68	2.5%
Average household size (members)	3.5	3.2	3.0	-1.4%
Urban population (% of total)	83%	84%	86%	-
Human Development Index	0.698	0.724	0.754	0.8%

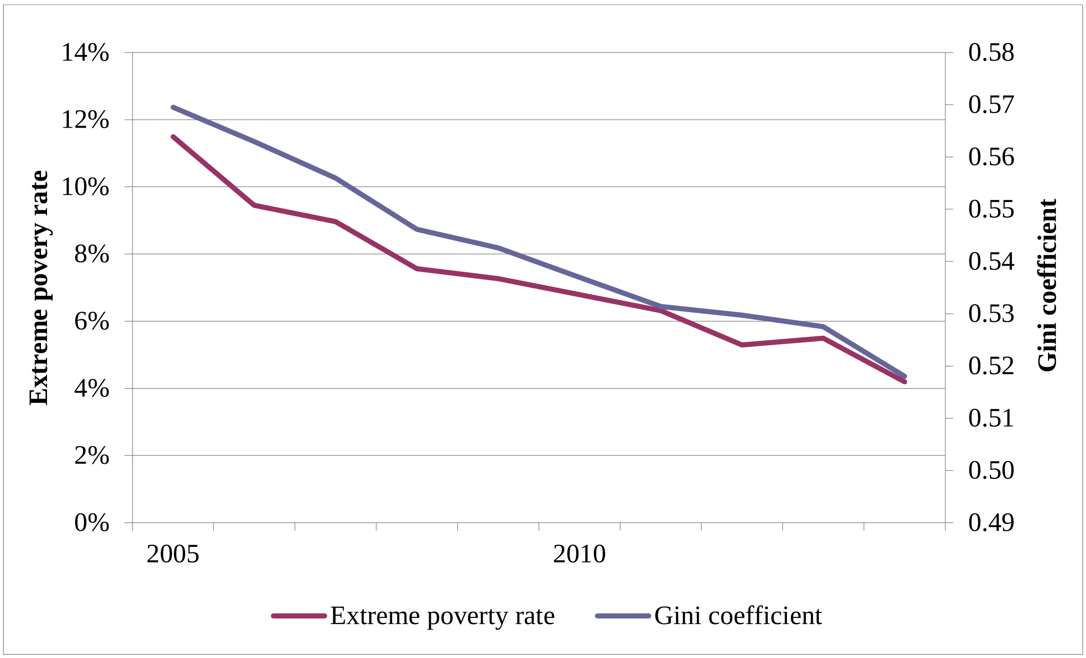
Source: IBGE (2013a, 2018), WORLD BANK (2018a) and UNDP (2016)

These policies were coupled with an increasing minimum wage policy and the expansion of governmental cash transfers programmes, namely *'Bolsa-Família'*, which consists of a monthly monetary aid to families with very low income levels[41]. According to NERI (2011 p. 120-121), the reducing wage gap between poor and rich workers (along with other work related issues such as labour market participation rates) explains approximately 66.9% of the inequality drop between 2001 and 2008. It is followed by the various social programmes, explaining 17% of the reduction, and social security benefits, with 15.7%. Figure 5.2 depicts the evolution of the Gini coefficient[42] for Brazil, the most commonly used index for measuring income inequality, and the share of population living under extreme poverty.

[41] Families benefiting from *'Bolsa-Família'* must comply with certain conditions. They have to prove children are attending school and up to date with vaccination.

[42] The Gini coefficient which varies from 0 to 1. In order to compute it, it is necessary to build a Lorenz Curve, which relates the cumulative share of the population to the cumulative share of the income earned. The area formed by the graph corresponds to the Gini coefficient. A Gini coefficient equal to 1 corresponds to the most unequal distribution possible, whereas a Gini coefficient equal to 0 denotes a situation in which all enjoy the same income level (see GINI (1909) and BARROS *et al.* (2006)).

Figure 5.2 - Extreme poverty rate[43] (%) and Gini coefficient evolution in Brazil from 2005 to 2015



Source: IPEA (2018a, 2018b)

A strong component of recent economic growth owes to boosted household demand. Apart from income gains, the expansion of credit allowed for the acquisition of durable consumption goods, namely household appliances and private vehicles. From the production side, a series of tax incentives allowed for lower prices at the same time as creating jobs in the industrial manufacturing sector. In fact, the heated domestic market acted as a ‘shield’ during the world economic crisis that burst in 2008. The Brazilian GDP decreased slightly in 2009 (-0.1%) and grew 7.5% in 2010, while the world economy experienced much worse rates (-1.7% in 2009 and 4.3% in 2010 (WORLD BANK, 2018b)).

Figure 5.3 shows the evolution of meat consumption, which is highly correlated to income[44], and Figure 5.4 shows motorization rates, both can be interpreted as a

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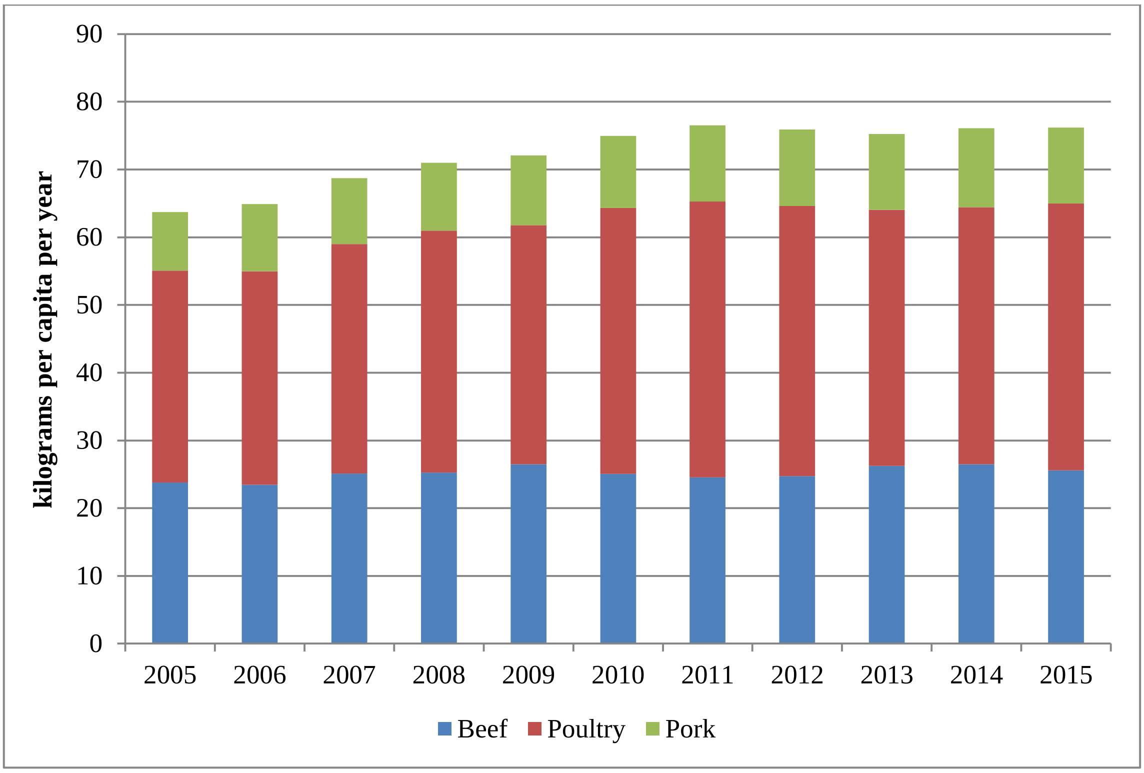
[43] Extreme poverty lined defined by an estimate of the value of a food basket with the minimum required calories to adequately supply a person based on FAO and WHO recommendations.

[44] See CAPPER (2012), CLARK AND TILMAN (2017) and GERBENS-LEENES AND NONHEBEL (2002).

reflexion of boosted income and consumption in the past decades. Annual meat consumption per capita standards in Brazil are much higher than in other BRICS countries (76.2 against 30.6 kilograms per capita per year in 2015), and even for the OECD average (66.8 kilograms per capita per year)[45].

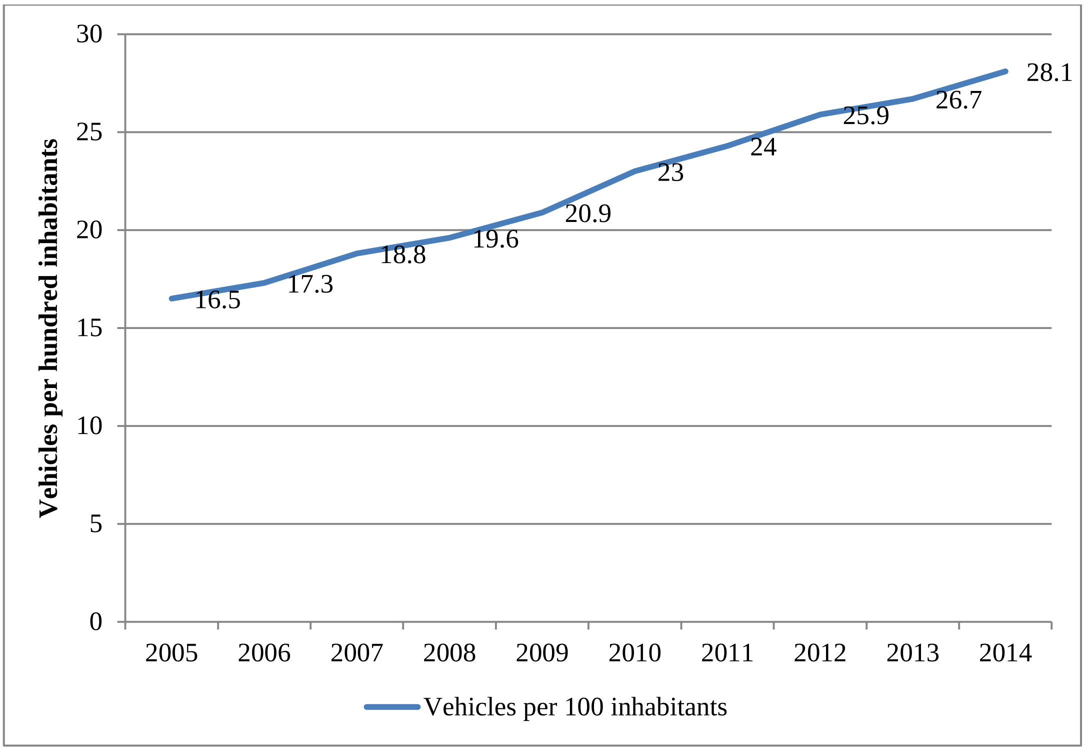
Figure 5.3 - Annual meat consumption evolution in Brazil from 2005 to 2015 (kilograms per capita)



Source: OECD (2018)

[45] Excluding sheep meat consumption, negligible in Brazil, but not in a few OECD countries.

Figure 5.4 - Motorization rate evolution in Brazil from 2005 to 2014 (vehicles per hundred inhabitants)



Source: OBSERVATÓRIO DAS METRÓPOLES (2015)

Evidently, impacts on residential energy use were not negligible. Between 2005 and 2015, electricity and natural gas demand increased at a much faster pace than the number of households, almost two times, as shown in

Table 5.2. Liquefied Petroleum Gas (LPG) evolved at a lesser pace because it is partially replaced by natural gas itself, which is supplied in the main urban centres. At the same time, demand for traditional biomass, usually applied in precarious cooking methods in rural areas, decreased.

Table 5.2 - Residential energy evolution in Brazil from 2005 to 2015

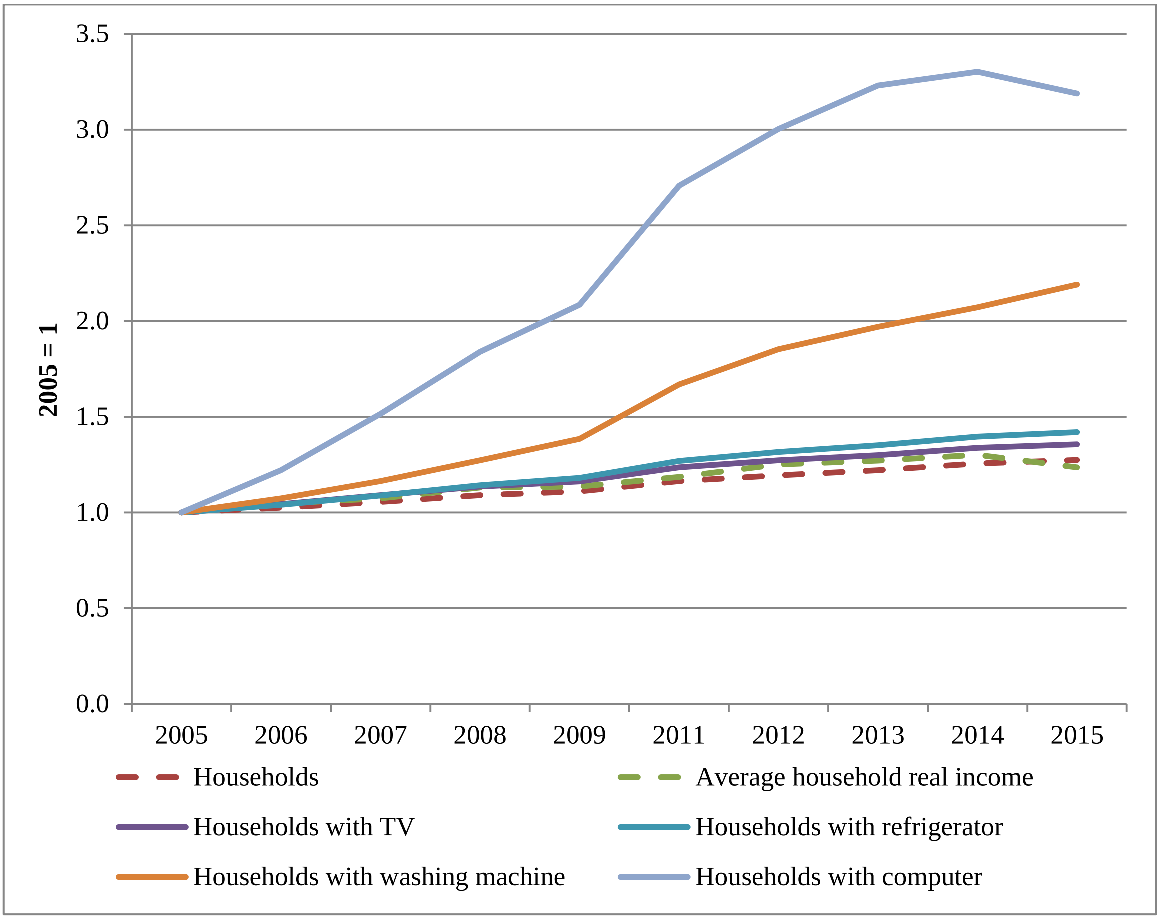
	2005	2010	2015	2005-2015 annual average variation (% p.y.)
Households (millions)	53.4	60.7	68	2.5%
Electricity (GWh)	83,193	108,457	131,315	4.7%
Natural Gas (million m^3)	217	290	354	5.0%
Liquefied Petroleum Gas (thousand m^3)	9,350	10,307	10,706	1.4%
Fuel wood (thousand tons)	26,564	23,471	20,431	-2.6%
Charcoal (thousand tons)	801	788	734	-0.9%

Source: EPE (2016)

The evolution of selected household appliances ownership rates, contrasted with total household and household income, supports the numbers above. For all of them, ownership rates grew above demographic indicators between 2005 and 2015[46]. In the case of television and refrigerator, it is clear that household ownership was already close to saturation in 2005. They almost reach the totality of households in 2015 (97% for television and 98% for refrigerator). In contrast, washing machine ownership rates increased from 36% to 61% and computer increased from only 18% to 46% in the same period.

[46] GROTTERA AND PEREIRA JR (2013) compare household monetary expenditures data from POF2002-2003 and POF2008-2009. They find that the greatest variation occurred in categories that impact energy consumption direct or indirectly, namely electricity, transportation and appliances.

Figure 5.5 - Evolution of households, household income and ownership of selected appliances in Brazil from 2005 to 2015 (2005=1)



Source: IBGE (2018)

Access to personal goods spread across the population, but other underlying aspects of living conditions still lag behind. Results from the 2013 National Household Sample Survey (PNAD) (IBGE, 2013b) show that even though the supply of basic services such as water supply, sewage and garbage collection systems improved, it did not happen as fast as the access to some durable consumption goods such as cell phones and domestic appliances. Comparing the poorest 20% and the richest 10% strata for the Brazilian population, the gap regarding the access to durable consumption goods is only 10 p.p., whereas the gap on the provision of basic services is about 60 p.p..

Moreover, it is clear that the consumption expansion cycle came to an end, either due to the political-economic crisis initiated in 2015 and its impacts on jobs and welfare, either because some of the country`s bottlenecks including low savings rate and infrastructure deficits made themselves finally – but not surprisingly – pronounced.

Brazil must face many challenges in order to sustain growth in the coming decades. The ageing population, owing to lower fecundity rates, should impact social security costs and create a workforce deficit. Combined with critically low investments in basic education and Research and Development (R&D), the country will hardly reverse the ongoing process of early deindustrialization pointed out by CHANG (2013) and DOMINGUES *et al.* (2017). Competition with East Asian and other Latin American countries is already marked. Brazil must pursue to modernize its industrial sector – seeking to incorporate future industrial trends such as automation and Artificial Intelligence, the internet of things, the use of big data and cloud storage systems, advanced materials and nanotechnology, energy storage, among others. Evidently, many of these technologies are applicable across the whole of the society, transforming daily lives, from consumption and labour supply choices to the way people interact with their peers and political leaders. Impacts on productive structure, income distribution, tax systems, trade and geopolitics are mostly unpredictable (for a literature on disruptive technologies and world trends linked to achieving climate goals, refer to HERWEIJER *et al.* (2017) and BLOK *et al.* (2016)).

It is nevertheless evident that keeping up with such transition will require creating and updating regulatory frameworks, training and capacity building, revision of tax systems and substantial investment in R&D. If Brazil fails to make such efforts, it risks remaining a commodity-based economy – dependent on international volatile markets. Moreover, this shall prevent the services sector to shift towards high-technology activities, remaining locked-in into low value added businesses.

Meanwhile, income inequality is still one of the highest in the world and regional disparities persist. The provision of basic services as public transportation and sanitation does not keep track of the expressive urbanization pace. Corruption and budgetary issues must also be addressed. In short, as many countries in the developing world, Brazil cannot neglect its social agenda. At the same time, reducing GHG emissions is imperative. The next section explores the Brazilian emissions profile, the challenges and opportunities to set and fulfil mitigation goals while bearing in mind development goals.

5.1.1 The Brazilian climate agenda

Brazil is a major player in agricultural commodities production, namely soybeans (BUSTOS *et al.*, 2015). It also accounts for the second largest cattle herd in the world (USDA, 2016). Pressure on land use is linked to this profile: deforestation, the main source of emissions in Brazil, is associated to the expansion of agricultural frontiers and demand for pastures. Agriculture and husbandry themselves are high-emitting activities, including non-CO_2 gases related mainly to enteric fermentation (bovines) and others. Apart from Brazil, few countries have the AFOLU sector as their main source of emissions, among them Indonesia and Peru (CLIMATEWATCH, 2018).

The Brazilian energy mix is favoured by a huge endowment of renewable energy resources. They account for nearly 40% of total energy. Renewables represent 75% of total electricity supply, in which hydropower stands out (EPE, 2016). The use of renewable biomass also contributes to a relatively clean energy sector. Mandatory blend shares for ethanol in gasoline (27%[47]) and biodiesel in diesel (currently 8%, expected to increase up to 10% in 2019[48]) were established, and nearly 11% of the Brazilian steelmaking industry uses charcoal instead of fossil fuels (see PINTO *et al.* (2018)).

Nonetheless, emissions related to the use of fossil energy have been increasing significantly, from oil products, natural gas and coal, driven by economic growth, the rising urbanization and the dominance of road transportation. Their share in power generation has also been increasing, in order to complement the use of the huge Brazilian hydropower potential (LA ROVERE *et al.*, 2014).

Emissions from industrial processes and waste are minor compared to the sectors mentioned above but, as for energy (see LUCENA *et al.* (2016)), they are expected to increase in accordance to urbanization rates, higher income and economic growth (CHEN *et al.*, 2013; LA ROVERE *et al.*, 2014; MARTÍNEZ-ZARZOSO; MARUOTTI,

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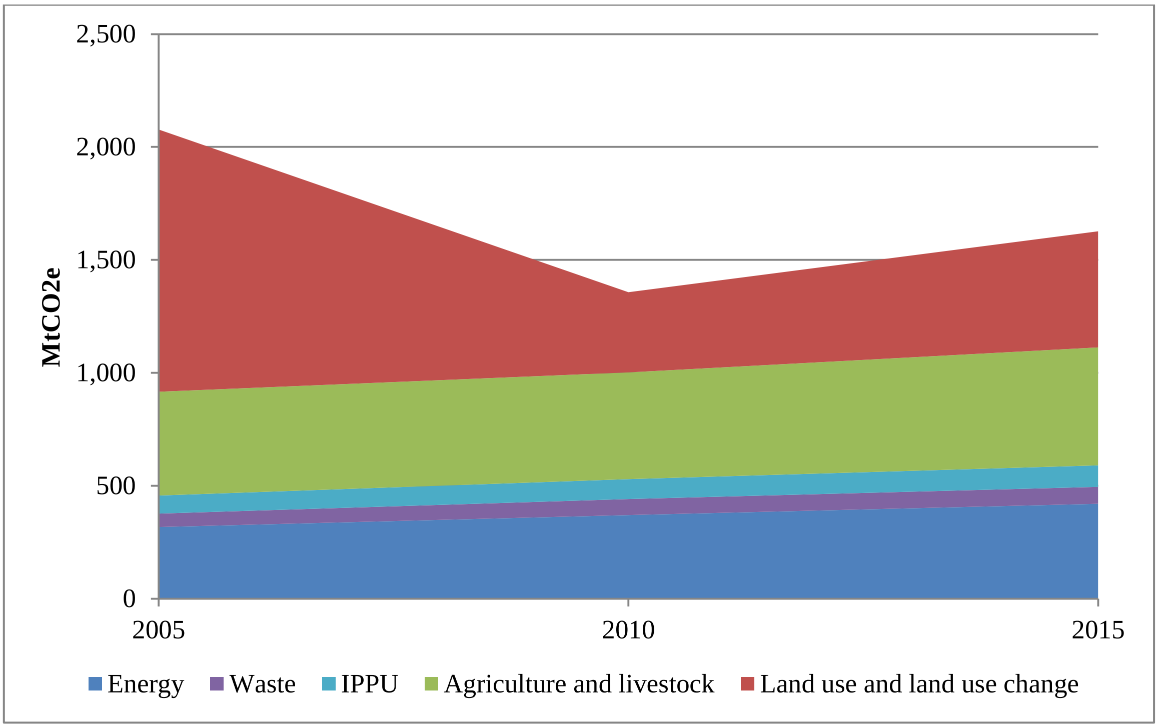
[47] See MAPA (2015).

[48] See BRASIL (2016).

2011). Figure 5.6 provides the Brazilian GHG emissions trajectory from 2005 to 2015 in megatons of carbon dioxide equivalent (Mt CO_2e)[49]

Figure 5.6 - Brazil greenhouse gases emissions profile evolution from 2005 to 2015 (MtCO2e)



Source: LA ROVERE *et al.* (2018) and MCTIC (2015)

Land use-related emissions dropped drastically, as a result of efforts to curb deforestation (see ASSUNÇÃO *et al.* (2015)). However, emissions from all other sources, which are mostly driven by economic growth, soared. While GDP grew at an annual rate of 2.4% between 2005 and 2015, energy emissions increased at higher rates (2.9% p.y.)[50], as shown in Table 5.3. Waste emissions evolved at similar to GDP rates. In the aftermath, emissions decreased despite economic growth, -2.4% p.y.. However,

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[49] Using Global Warming Potential 100 from IPCC Fifth Assessment Report (AR5) (IPCC, 2014).

[50] This is in line with BURKE AND CSEREKLYEI (2016), whose findings report high energy-GDP elasticities for transport, industry and services sectors. According to (EPE, 2016), the transport and industrial sectors accounted for nearly 69% of total energy final consumption.

Brazil still figures among the main emitters in the world, the seventh in 2014 (CLIMATEWATCH, 2018).

Table 5.3 – Brazilian GHG emissions profile evolution from 2005 to 2015 (MtCO2e)

	2005	**2010**	**2015**	**2005-2015 annual average variation (% p.y.)**
Energy	317	370	420	2.9%
Land use and land use change	1,161	355	514	-7.8%
Agriculture and livestock	460	473	522	1.3%
Waste	60	71	75	2.3%
IPPU	80	88	95	1.8%
Total	**2,077**	**1,357**	**1,627**	**-2.4%**

Source: MCTIC (2010)

Reducing global GHG emissions is certainly of interest for Brazil. Average temperature rises may cause the savanization of the Amazon biome, and the desertification of the other important ones, as well as increase the occurrence of extreme weather events (MARGULIS *et al.*, 2010). Moreover, most mitigation options present a set of co-benefits, both related to conservation (in the case of LULUCF and agricultural sectors) and to health and lifestyles improvements (in the case of energy, especially the transportation sector) (RENNKAMP; BOULLE, 2017).

In 2015, Brazil presented its Intended Nationally Determined Contribution for the 21st Conference of the Parties in Paris (COP21). The pledge consisted of an economy-wide, absolute mitigation target, with a long-term horizon. Brazilian emissions level should reach 1.3 $GtCO_2e$ in 2025 and 1.2 $GtCO_2e$ in 2030, representing a reduction of 37% and 43% compared to 2005 (2.1 $GtCO_2e$), respectively. Per capita emissions should reach approximately 6.2 tCO_2e in 2025 and 5.4 tCO_2e (GWP-100; IPCC AR5) in 2030, corresponding to an estimated reduction of 66% in terms of greenhouse gas emissions per unit of GDP in 2025 and of 75% in 2030, in relation to 2005.

Briefly, the Brazilian NDC (BRAZIL, 2015) aims to:

- increasing the share of sustainable biofuels in the Brazilian energy mix to approximately 18% by 2030 (including advanced biofuels);

- in the electricity sector, increasing the share of renewables other than hydropower in the power supply to at least 23% by raising the share of wind, biomass and solar and 10% efficiency gains by 2030;

- in the land use and forestry sector, strengthening and enforcing the implementation of the Forest Code, achieving zero illegal deforestation in the Brazilian Amazonia and restoring 12 million hectares of forests by 2030, among other actions;

- in the agriculture sector, strengthening the Low Carbon Emission Agriculture Program (Plano ABC), restoring degraded 15 million hectares of degraded pasturelands and expanding 5 million hectares of integrated cropland-livestock-forestry systems by 2030;

- in the industry sector, promoting new standards of clean technology, enhancing energy efficiency and expanding low carbon infrastructure;

- in the transportation sector, promoting efficiency and improving infrastructure for transport and public transportation in urban areas.

The NDC also references policies and measures related to adaptation, even though no quantitative targets are provided. They include building resilience of populations, ecosystems, infrastructure and production systems, by reducing vulnerability and through the provision of ecosystem services, enhancing capacity in water security and the conservation and sustainable use of biodiversity.

5.1.2 Linkages between mitigation and Sustainable Development Goals (SDGs)

It is underlying that synergies between climate and development agendas are explored. As pointed out by GARIBALDI *et al.* (2013), mitigation actions that simultaneously address poverty and development have a better chance of being implemented. As RAO *et al.* (2014) vindicate, improving access to basic needs such as nutrition and water supply to the lower population strata – actions explicitly announced in SDGs 2 and 6, respectively - would require lower increases in greenhouse gas emissions than a broad increase in affluence (closely related to income and ultimately to consumption, lifestyles and energy use). However, policies seem to still be trapped into the pursuit of a growth-oriented, energy-demanding development nexus. In this case, one should not expect a strong decoupling between the HDI and energy consumption (see STECKEL *et al.* (2013)).

Mutually reinforcing actions should be prioritized under the scope of the NDC. In fact, many actions communicated in the Brazilian NDC have strong linkages to the Sustainable Development Goals announced for the 2030 United Nations agenda (see UN (2015b)). Increasing the share of renewable energy and energy-efficiency targets relate mainly to SDG7 (Affordable and clean energy), whereas improving agricultural techniques and all land use-related actions connect to SDG2 (Zero hunger) and SDG15 (Life on Land). Enhancing resilience and public transport access has a strong link with SDG11 (Sustainable cities and communities) and developments in efficiency, resilient infrastructure and advanced biofuels contemplate SDG9 (Industry, innovation and infrastructure). Access to sanitation and water security are explicitly related to SDG6 (Clean water and sanitation). Expanding low carbon infrastructure and improving resilience of systems are associated to SDG8 (Decent work and economic growth).

Indeed, many synergies can be identified between the declared NDC actions and the SDG, including those related to adaptation. In a broader sense, they also link to SDG1 (No poverty), SDG3 (Good health and wellbeing), SDG5 (Gender equality) and SDG10 (Reduced inequalities). However, an analysis performed by BRANDI *et al.* (2017) did not find explicit mentions to SDG4 (Quality education), SDG12 (Responsible consumption and production) (e.g. no actions with specific focus on recycling or waste reduction), SDG14 (Life below water) and SDG16 (Peace, justice and strong institutions).

Since 2016, the decreasing deforestation trend has been reversed (see INPE (2018) for deforestation rates in the Brazilian Amazon), as a result of a weakening of underlying institutions to monitor activity, including budget cuts. In contrast, absolute emissions from energy and industry were lower than previously estimated due to economic recession. Weak market and political signals have been recently provided, aggravated by uncertainty arising political instability. As a result, Brazil`s ability to meet its NDC goals is at stake, and so are the many social and environmental benefits that could arise from their compliance.

5.1.3 Greenhouse Gases Emissions Targets

According to the UNEP Emissions Gap Report (UNEP, 2016), stabilizing GHG emissions at levels consistent with a 1.5^oC target require global emissions to reach 8 $GtCO_2e$ in 2050. As world population prospects (UN, 2015a) indicate a global population of 9.7 billion people in 2050, the corresponding global per capita emissions level should be 0.82 tons of CO_2e.

In the Brazilian context, with national population reaching 226 million people in 2050, total domestic emissions should not exceed 186 $MtCO_2e$ in 2050 to be compatible with such target, not taking into account burden sharing aspects. Table 5.4 provides the figures for such calculations (including those corresponding to a 2^oC stabilization target).

Table 5.4 - Emissions Gap Report world scenarios and pathways for Brazil based on world GHG emissions per capita compatible with 2ºC and 1.5 ºC stabilization targets

		2020	**2025**	**2030**	**2050**
	World Population (millions)	7,758	8,142	8,501	9,725
	Brazilian Population (millions)	212	218	223	226
2°C target	World Emissions[51] ($GtCO_2e$)	52	48	42	23
	World Emissions per capita (tCO_2e per capita)	6.7	5.9	4.9	2.4
	Brazilian Emissions ($GtCO_2e$)	1.421	1.287	1.102	0.535
1.5°C target	World Emissions[52] ($GtCO_2e$)	56	47	39	8
	World Emissions per capita (tCO_2e per capita)	7.2	5.8	4.6	0.8
	Brazilian Emissions ($GtCO_2e$)	1.531	1.260	1.024	0.186

Source: LA ROVERE *et al.* (2018) based on UNEP (2016), UN (2017), and IBGE (2013a)

5.2 Overview of scenarios

This analysis considers three scenarios up to 2050. The first scenario is the base case, followed by a set of two alternative pathways that seek to reduce GHG emissions through demand-side action, described below.

- Reference scenario (REF): this scenario incorporates current mitigation policies approved and adopted by the government and the business sector that are underway in the Brazilian long-term governmental strategy. They range from deforestation goals, biofuel development, and efficiency gains in energy and agriculture, among others. It contemplates the full implementation of the Brazilian Nationally Determined

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[51] Pathways limiting warming to below 2°C by 2100 with >66% probability - Limited action until 2020 and cost-optimal mitigation afterwards.

[52] Pathways limiting warming to below 1.5°C by 2100 with >50% probability - Limited action until 2020 and cost-optimal mitigation afterwards

Contribution (NDC) under the scope of the Paris Agreement up to 2030, and its continuity from 2030 to 2050 with no further increase in ambition.

- Lower GHG emission lifestyle scenario (LES): this scenario assumes a more environmentally sound household behaviour regarding energy, transport, food and appliances consumption, as well as waste generation. Households seek a dematerialized lifestyle, prioritizing culture, education, leisure, etc. over physical goods. Lifestyle changes in mobility, diets, energy conservation and consumption shift from material goods towards cultural services.

- Lower GHG emission lifestyle with increased trade scenario (LES-Tr):
This scenario is similar to the previous one, except that, in this case, resource-intensive sectors seek to offset their reduced internal demand by boosting trade activity. The oil, liquid fuels, agriculture and industrial sectors manage to increase exports, due to international competitiveness.

5.3 Scenarios drivers

This section describes the main assumptions regarding population, energy prices, factor productivity, economic growth, income and consumption trends, among others, for the reference scenario. Apart from particular assumptions relative to household behaviour, demographic and macroeconomic trends are common to all scenarios. Differences in consumer preferences specific to the alternatives pathways are discussed next (section 5.3.2). It is important to highlight that possible impacts on productivity and availability of resources and factors arising from climate change are not taken into account.

5.3.1 Reference scenario

The reference projection is based on the Governmental Planning Scenario (GPS) from the IES-Brasil 2050 exercise (LA ROVERE *et al.*, 2017). This is a comprehensive study in which the Imaclim model is coupled with bottom-up modules (see Figure 4.11) for the following sectors:

- Transport (D´AGOSTO *et al.*, 2017 in LA ROVERE et al. (2017))
- Energy supply (CUNHA *et al.*, 2017 in LA ROVERE et al. (2017))
- AFOLU (excluding energy demand) (WALTER *et al.*, 2017 in LA ROVERE et al. (2017))
- Waste (DUBEUX; COLLING, 2017 in LA ROVERE et al. (2017))
- Industry (SANTOS *et al.*, 2017 in LA ROVERE et al. (2017))
- Residential (WEISS; PEREIRA JR., 2017a in LA ROVERE et al. (2017))
- Services (WEISS; PEREIRA JR., 2017b in LA ROVERE et al. (2017))
- Agricultural energy (WEISS; PEREIRA JR., 2017c in LA ROVERE et al. (2017))

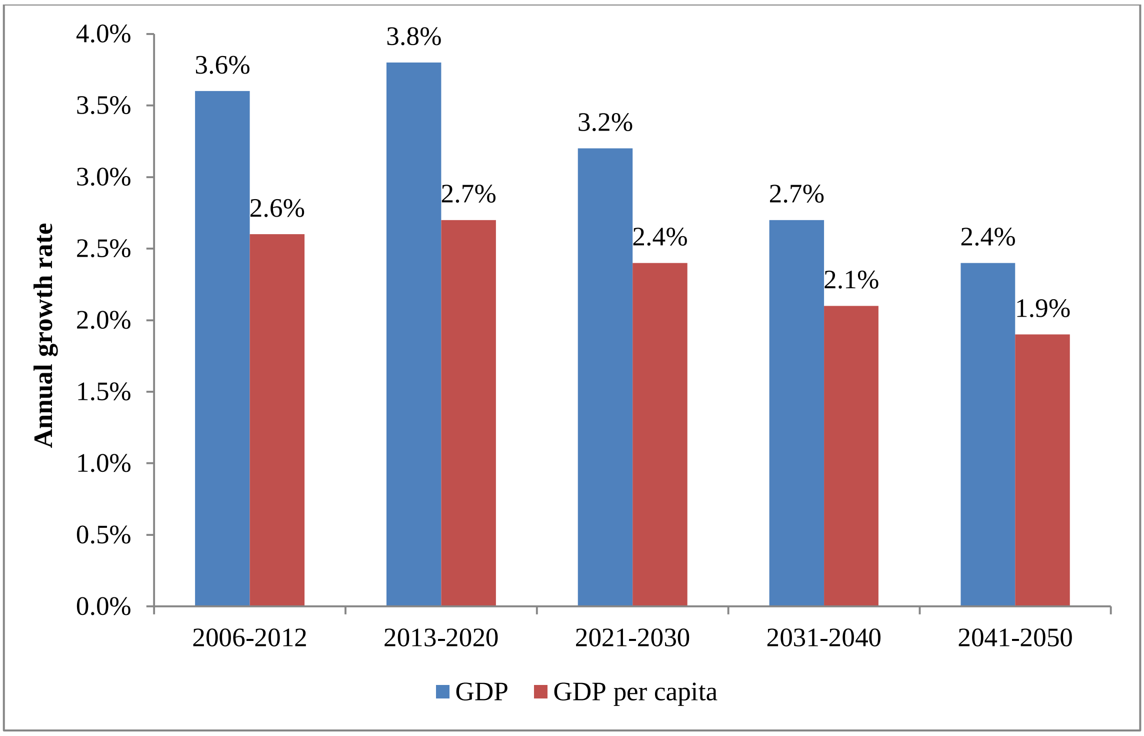
The GPS is based on the 2050 National Energy Plan, henceforth referred to as PNE 2050 (EPE, 2014a), the most relevant long-term strategy report available for the Brazilian economy, with a special focus on energy planning. However, it does not replicate entirely the PNE 2050 assumptions, since they assume relatively high GDP growth rates both for Brazil and the rest of the world, which were reviewed due to recent events, such as the political-economic crisis in Brazil. Global economic growth and energy prices projections were also reevaluated. The rectified growth rates were properly agreed upon by a Scenario Building Team (SBT) composed by stakeholders from the government, private sector, academia and civil society (LA ROVERE *et al.*, 2017).

The following sections detail and discuss such assumptions. But first, it is important to highlight that this scenario is not a ‘business-as-usual’ scenario, as it includes the mitigation efforts present in the Brazilian NDC announced in Paris during COP21 up to 2030, and their extension up to 2050. It is also worthy to highlight that, in this thesis, consumption patterns converge according to income evolution. This is one of the main contributions of this thesis to literature, given its specific focus on household demand. In IES-Brasil 2050, these aspects were not explored in such depth, so household demand is defined by past trends (see section 3.7 for a discussion on this topic).

5.3.1.1 World trends

The global activity level evolves rapidly in the period between 2013 and 2020, 3.8% per year on average, driven by growth in emerging economies, while developed countries continue to recover from the economic crisis that began in 2008. After 2020, there is a slowdown in growth, due to reduced growth rates in China and other emerging countries. Figure 5.7 provides growth rate ranges for different periods up to 2050.

Figure 5.7 - World annual average growth rate by decade (% p.y.)



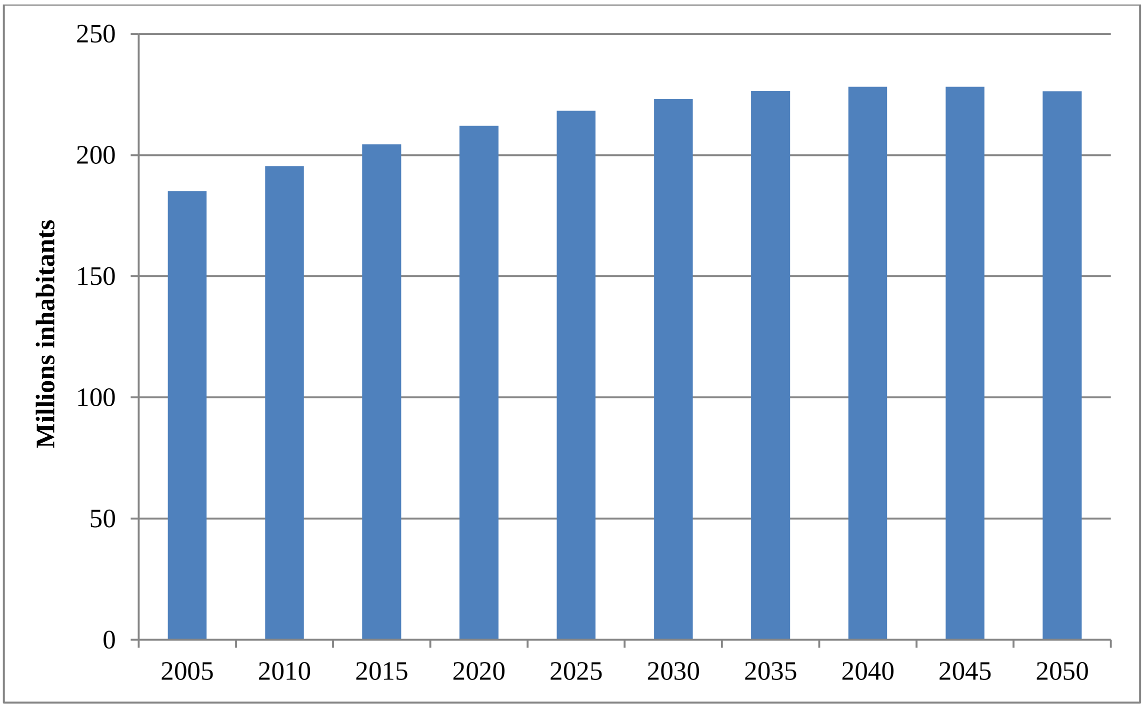
Source: EPE (2014a)

Between 2016 and 2050, the price of oil (Brent) is considered to recover up to 85 US$/barrel (constant prices of 2013), in line with IEA low-oil price scenario (IEA, 2015). Determinants of this price level include: i) recovery in world economic growth; ii) maturity of oil and gas projects (particularly with non-conventional resources); iii) peak production of shale/tight US oil, estimated at around 2020; iv) increased competition from other substitute sources (including renewable and unconventional natural gas, especially shale/tight gas); v) reducing the share of oil's role as speculative financial assets and vi) gradual increase in energy efficiency and substitution by other sources. Oil prices in Brazil are determined internationally, as well as natural gas and coal prices.

5.3.1.2 Domestic trends

Population growth is expected to slow down at intensified rates, due to lower fecundity rates. Population peaks between 2040 and 2045 and reaches 226 million people in 2050. People in working age represent a decreasing share of total population. Shrinking active population leads to a lower natural unemployment rate in 2050, around 7.5%.

Figure 5.8 - Brazilian population evolution prospects from 2005 to 2050 (millions inhabitants)



Source: IBGE (2013a)

The domestic macroeconomic environment is characterized by improved infrastructure, reducing transportation costs and increasing the competitiveness of productive sectors. Greater investments in education, including revenues from the exploitation of the pre-salt layer, and a social security reform in order to stabilize deficit to GDP in 2005 standards are also presumed.

Brazil grows at lower rates compared to the world average until 2020, when it recovers from the current crisis. Between 2021 and 2030, effects of reforms put in place in the previous decade enable the country to grow along with the rest of the world. Between 2030 and 2050, Brazil grows at slightly slower paces, yet at a faster pace than global rates. From base year up to 2050, the average growth rate is 2.7% p.y..

Services are expected to account for a growing share of the economy, whereas industrial sectors lose participation, for reasons discussed in section 5.1. The agricultural sector also increases its share in GDP due to productivity gains, land availability and its relevance for trade balance. With the growing exploitation of pre-salt reserves, oil extraction is expected to reach 5 million barrels per day in 2050. The bulk of new resources should be destined for exports and, by the middle of the century, Brazil becomes a net exporter of oil. A share of oil revenues is invested in education and health, with positive implications in overall productivity.

As investment in education increases, productivity and competitiveness are boosted. Due to an enhanced business environment, labour informality drops, whereas the wage gap between skilled and non-skilled workers keeps narrowing. Governmental cash transfer programmes such *'Bolsa Família'* continue and income inequality keeps decreasing among different income classes, with Gini coefficient reaching a similar level to less wealthy European countries in 2005. Factor productivity evolution is consistent with these assumptions: labour productivity increases at the same time sectors become more intensive in capital[53].

5.3.1.2.1 Household trends and converging consumption patterns

PNE 2050 provides the main drivers regarding the expected evolution of Brazilian households` socio-demographic and cultural characteristics, related to higher urbanization, smaller household size (due to higher income and decreasing fecundity rates) and technological progress.

[53] For the sake of simplification, factor productivity (labour, capital and land) is assumed to evolve equally for all productive sectors. Autonomous energy efficiency improvement (AEEI) is also considered.

Table 5.5 - Brazilian households` characteristics projections

	2005	2010	2020	2030	2040	2050
Population (millions)	185	195	212	223	228	226
Households (millions)	52.9	60.0	72.8	82.0	92.0	99.0
Urban households (%)	85%	86%	86%	88%	88%	89%
Average household size (members)	3.5	3.3	2.9	2.7	2.5	2.3

Source: Author`s elaboration, based on EPE (2014a)

5.3.1.3 Converging consumption patterns among households

A complementary premise – especially relevant while assessing household behaviour - is that as income per capita converges across income classes, consumption patterns will converge as well, leading to a potentially higher demand for goods and services and consequently, higher emissions (CORNILLIE; FANKHAUSER, 2004; DURO; PADILLA, 2011; EZCURRA, 2007; MARKANDYA *et al.*, 2006; MIELNIK; GOLDEMBERG, 2000; MIKETA; MULDER, 2005; NILSSON, 1993).

In fact, with the assumed growth rates and improved income distribution, one can identify how household classes' level of income evolves in the assessed timeframe, and thus, how should their consumption preferences evolve as well.

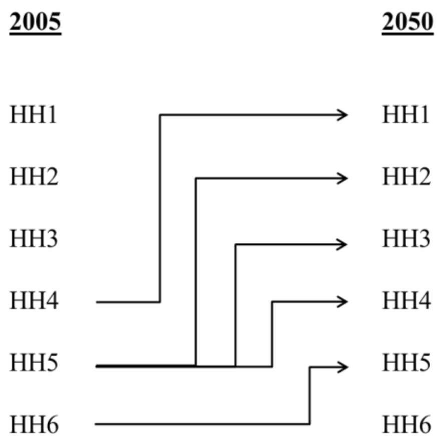
As explained in section 3.7, using observed data from the past to estimate elasticities for simulating households` preference in a long-term horizon is not adequate. Therefore, a preliminary simulation incorporating the drivers and assumptions described above was performed in order to estimate the evolution of each class level of income. It serves as the basis for identifying the (partial) income convergence among classes and defining how they allocate their consumption budget in 2050 accordingly.

Table 5.6 - Preliminary assessment of real consumption income evolution (R$2005) and definition of benchmark for 2050 consumption structure

	2005	2050	Variation (%)	Income in 2050 (convergence criteria)
HH1	2.2	9.4	327%	1.33x HH4 income in base year
HH2	3.2	12.7	297%	1.09x HH5 income in base year
HH3	4.8	14.8	208%	1.27x HH5 income in base year
HH4	7.1	21.0	196%	1.80x HH5 income in base year
HH5	11.7	29.9	156%	1.13x HH6 income in base year
HH6	26.4	67.8	157%	2.57x HH6 income in base year

Source: Author`s elaboration

Figure 5.9 - Consumption convergence among income classes between 2005 and 2050



Source: Author`s elaboration

The lowest decile income surpasses the fourth`s level of income in 30% in 2050. For the three next classes, income converges with HH5 in 2050, exceeding its base year levels in 9%, 27% and 80%, respectively. The fifth class, in its turn, attains a level of income that is 13% higher than that of HH6 in 2005. Finally, the top class` level of income increases more than twofold compared to its own initial level.

In the reference scenario, classes are expected to allocate their budget correspondingly, that is, the same way as the specific class to which their income converges in this preliminary exercise, proportions kept.

Complementarily, a set of assumptions were made in order to calibrate household behaviour in the reference scenario, combined with trends already taken into account, like efficiency gains, smaller household size, appliance usage, among others. They concern societal upcoming changes that may affect consumption choices, especially regarding energy demand. Furthermore, they are particularly relevant to describe the richest household preferences, for which, unlike the other classes, there is no benchmark to beacon. Such assumptions are described next, using PNE 2050 and numerous other sources.

5.3.1.4 Household consumption assumptions

Household energy demand

PNE 2050 outlines the household energy consumption for Brazilian households up to 2050. Ownership rates, usage levels and efficiency gains are discussed for:

- Lighting (incandescent, fluorescent and LED bulbs)
- Food conservation (fridges and freezers)
- Air conditioning (fans and air conditioners)
- Water heating (electric, LPG, natural gas and thermosolar shower)
- Cooking (LGP, natural gas, firewood, charcoal and electric stoves)
- Other uses (miscellaneous appliances, mainly related to information, communication and leisure)

PNE 2050 levels of household energy demand are presented in Table 5.7, and the final figures considered in this exercise are presented next, for all consumption categories.

Table 5.7 - Residential energy consumption (ktoe)

	2005	2050
Electricity	7,155	28,891
Natural Gas	191	4,075
Liquefied Petroleum Gas	5,713	7,675
Fuel wood	8,235	2,372
Charcoal	517	225

Source: Author`s elaboration, adapted from EPE (2006, 2014b)

Biomass

Overall biomass consumption increases approximately 2.5% p.y., based on PNE 2050, with sugar cane ethanol accounting for an increasing share of it, 93% in 2050 (Table 5.8). Traditional biofuels used for cooking are replaced by LPG (which, in its turn, is substituted by natural gas in urban centers). Fuel wood and charcoal levels are slightly higher than in PNE 2050, due to lower growth and income per capita levels, which prevent traditional biomass to be replaced by LPG at such speed.

Table 5.8 - Disaggregation of biomass sector in 2050, per source (%)

	Share in 2050
Ethanol	93.5%
Fuel wood	6.0%
Charcoal	0.5%

Source: Author`s elaboration based on LA ROVERE *et al.* (2017)

Allocation among households classes was determined by the level of income in 2050, supplemented by assumptions made based on WINROCK (2007) and microdata from the 2009 PNAD (IBGE, 2009) for fuel wood and charcoal (Table 5.9).

Table 5.9 - Share of fuel wood and charcoal consumption per class in 2050 (%)

	HH1	HH2	HH3	HH4	HH5	HH6
Share in consumption	33%	18%	12%	7%	2%	1%

Source: Author`s elaboration based on WINROCK (2007) and IBGE (2009)

Natural Gas

In 2050, nearly 90% of total households are expected to be in urban areas, where natural gas supply increases exponentially. It is used not only for cooking purposes (replacing LPG) but also for water heating. Residential consumption evolves at a 4.8% p.y. rate (yet below PNE 2050 rates, due to lower growth rates).

Oil products[54]

The demand for fossil fuels for transportation (mainly gasoline) evolves at a lesser pace compared to biomass, since they are partially replaced by ethanol in light-duty vehicles. Analogously, liquid fossil fuels for residential energy (LPG) are replaced by natural gas, and substitute traditional biofuels for cooking. Household demand for oil refined products grows less than other energy sources, around 2.1% p.y.. Gasoline represents an increasing share of it, as lower income classes purchase private cars, at the same time they do not need to increase as much their level of LPG consumption, which approaches saturation.

[54] Fuels for transportation may also include diesel, whereas for residential energy uses they may include kerosene. It was considered that the share of these products is negligible in household demand in 2050.

Table 5.10 - Disaggregation of oil products in 2050, per source (%)

	Share in 2050
Gasoline	86%
LPG	14%

Source: Author`s elaboration based on LA ROVERE *et al.* (2017)

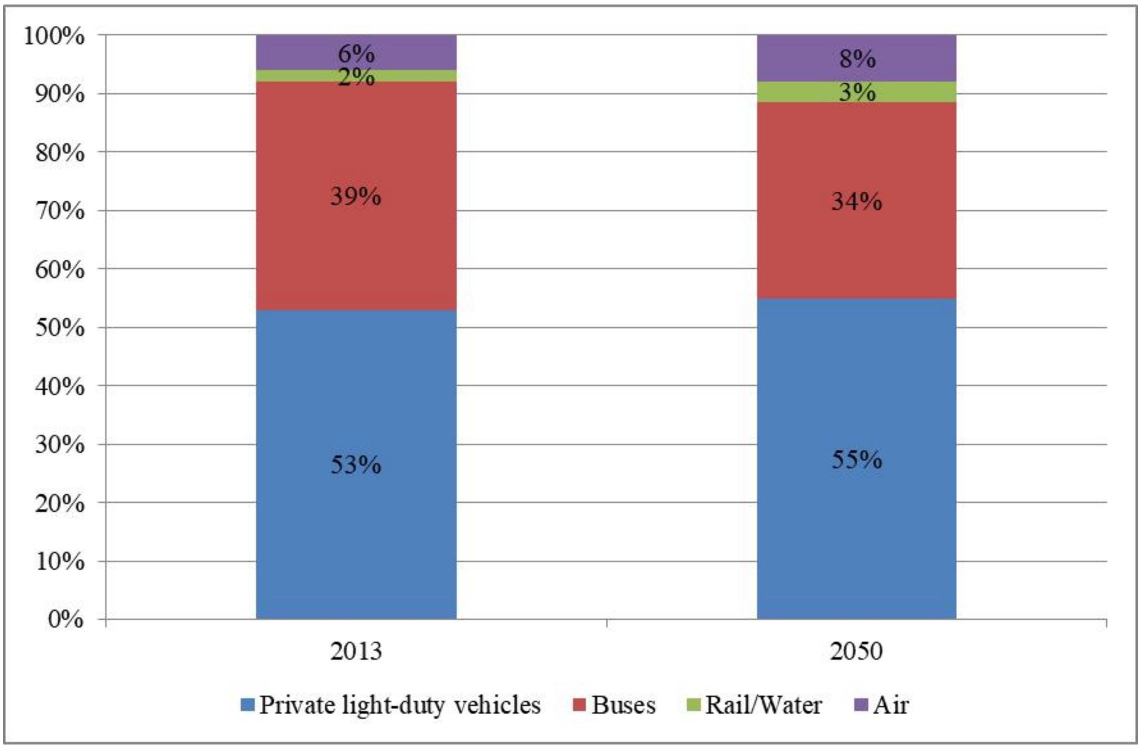
Electricity

Electricity consumption in the residential sector is expected to increase, driven by higher ownership rate for domestic appliances, as well as computers, cell phones and other equipment related to information and entertainment. Electricity demand increases 1.7% p.y., which is, again, lower than PNE 2050 estimates. Per capita residential levels in 2050 reach around 1,150 kWh/year. The richest income decile`s demand is similar to France national average in 2010 (2490 kWh/capita/year) (BARBIER *et al.*, 2018).

Public Transport

PNE 2050 also contemplates trends in passenger transportation, favoured by income gains, urbanization and infrastructure investment. Motorization rates reach levels similar to developed countries in 2050, approximately 1.7 inhabitant per vehicle. Private transportation is expected to account for an increasing share of passenger mobility (55% in 2050 – see Figure 5.10), as discussed previously.

Figure 5.10 - Modal share in passenger transportation in 2013 and 2050 (%)



Source: EPE (2014b)

Total passenger momentum per capita (private and public) is defined according to GIROD *et al.* (2013b), estimated at up to 15.4 thousand pass.km in 2050, from which 53% are met by private cars. For public transportation specifically, national average in 2050 is approximately 2.5 times higher than base year, but below current European standards[55].

Food

Food consumption within the household increases at lower rates than for other goods and services and significantly below income gains. This occurs because

[55] France national average for public transportation in 2010 was 13.3 pass.km per capita (BARBIER *et al.*, 2018).

households, even low-income ones, are close to saturation in base year[56]. It was arbitrarily defined that top decile households do not exceed 30% of HH6 2005 consumption level for this category.

Other goods

This category comprises durable consumer goods. Hence, consumption levels grow substantially for lower income classes. As for food, a limit of 30% increase above base year levels was set for the richest households in the energy-intensive industrial goods category (comprising goods for household maintenance and hygiene items). For manufactured (non-energy-intensive) goods (private vehicles, electric appliances, clothes and personal effects, among others) the limit was set at 60% above base year levels.

Services

Once defined the expected consumption for all other categories, the remaining budget is allocated in the Services category. Due to its residual feature, no assumptions are required to define 2050 consumption levels. As anticipated, consumption levels increase substantially for all classes. For richer households, it increases more than any other category.

5.3.1.5 Final consumption structure per income class

Different budget shares per income class are presented next, for initial and final years. As discussed above, income converges: income increases at higher rates for bottom classes than for tops ones.

[56] According to data from the 2008 National Household Survey, the average daily intake in Brazil in 2008 was 2,044 kcal per person (ranging from 1,490 for female elders to 2,289 to male teenagers). The average is close to World Health Recommendation levels of approximately 2,000 kcal per day (IBGE, 2011).

In general, households saturate their level of consumption of basic goods and services, such as electricity, transportation and food, deploying a lesser share of their budget to such needs. Evidently, this happens at a greater extent among richer households. Lower income ones actually increase their budget share devoted to oil products, electricity and consumer goods (sector ‘Rest of industry’), for example, once they have better access to private vehicles and appliances. Tables below present the consumption budget share per class in base year and in 2050 for the reference scenario.

Table 5.11 - Expenditures budget share per class in 2005 (% of household consumption income)

	HH1	HH2	HH3	HH4	HH5	HH6
Biomass	2.0%	1.6%	1.2%	1.0%	0.6%	0.4%
Natural Gas	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Oil products	0.7%	0.9%	1.3%	2.3%	3.7%	4.2%
Electricity	1.8%	1.9%	2.2%	2.1%	1.8%	1.3%
Public transportation	4.9%	5.1%	4.9%	4.8%	4.2%	3.8%
Livestock	0.1%	0.1%	0.1%	0.1%	0.0%	0.0%
Agriculture and agroindustry	33.6%	29.0%	23.4%	20.1%	14.3%	9.8%
Energy intensive industry	6.6%	6.6%	6.3%	6.4%	5.6%	4.7%
Rest of Industry	10.4%	11.3%	12.3%	13.9%	16.3%	17.0%
Services	40.0%	43.5%	48.2%	49.4%	53.4%	58.7%
Total	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

Source: Author`s elaboration

Table 5.12 - Expenditures budget share per class in 2050 – REF (% of household consumption income)

	HH1	HH2	HH3	HH4	HH5	HH6
Biomass	1.7%	1.3%	1.1%	0.8%	0.6%	0.3%
Natural Gas	0.1%	0.1%	0.1%	0.1%	0.0%	0.0%
Oil products	2.4%	2.2%	2.3%	3.6%	4.1%	3.4%
Electricity	2.1%	1.9%	1.9%	1.9%	1.7%	1.1%
Public transportion	4.6%	4.1%	4.1%	4.1%	3.7%	2.3%
Livestock	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Agriculture and agroindustry	19.9%	16.9%	17.0%	11.9%	9.7%	4.6%
Energy intensive industry	6.4%	5.6%	5.6%	5.6%	4.7%	3.1%
Rest of Industry	13.8%	16.2%	16.2%	16.2%	16.9%	10.2%
Services	48.9%	51.7%	51.7%	55.7%	58.5%	75.0%
Total	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

Source: Author`s elaboration

The national average per capita GDP in base year was 4,760 2005 US$, increasing to 13,110 2005 US$ in 2050 in the reference case[57]. The estimated budget share in 2050 seems to be relatively in line with similar analysis performed for other developing countries. DAI *et al.* (2012) estimate Engels curves for Chinese households in 2050. In their model, per capita expenditure for urban households in 2050 is 12,608 2005 US$. Even though comparison is hindered by aggregation choices (the authors split households into urban and rural, and expenditures categories are also fairly different than in the tables above), some common trends are identified. Budget shares devoted to food and housing decrease, while people spend more on clothing, furnishing, communications and transport (reflecting higher car ownership rates and passenger

[57] Using the observed 2005 exchange rate of 2.43 R$ per US$, which can be considered low. An exchange rate at approximately 3.15 R$ per US$ in 2050 as in LA ROVERE et al. (2017) should be more realistic.

activity). However, in their estimation households devote a lower share of expenditures to services, while the opposite occurs for clothing and furnishing.

5.3.2 Alternative pathways

In the alternative pathways, households seek to lower their overall carbon footprint associated with consumption. The considered consumer strategies include ambitious, but technically and socioeconomically feasible practices that can be mostly pursued at a daily basis.

5.3.2.1 Lower GHG emissions lifestyles scenario (LES)

In this scenario, households pursue a strong dematerialization of consumption and waste reduction, focusing on well-being, culture and education over physical goods. Environmental attitudes which promote resource conservation from the demand side take place in various aspects of daily life (effects of behaviour shifts are detailed in Table 5.14), such as:

Household energy

Improved energy saving behaviour within the household lead to a 15% reduction in electricity demand and a 10% reduction in natural gas and liquefied petroleum gas demand, based in GIROD AND DE HAAN (2009)[58]. Actions include switching off stand-by, turning off appliances when not needed, washing clothes at full loads and with cold water, reducing duration of showers and optimizing cooking habits.

[58] GIROD AND DE HAAN (2009) find that Swiss households with the lowest GHG emissions per capita account for a carbon footprint 45% lower than average for living (1,354 kg CO_2 per year against 2,994 kg CO_2 per year). Regarding electricity consumption, their footprint is 40% lower than average (348 kg CO_2 per year against 860 kg CO_2 per year). We use their study to mark our assumptions, considering that the grid emissions factor is the same for all households.

Transportation

Existing literature argues global climate targets can hardly be met with current light-duty vehicle usage levels (intense in high-income countries and rapidly increasing in low-income ones). Demand avoidance options are likely essential (GRIMES-CASEY *et al.*, 2009; JOHANSSON, 2009; SAGER *et al.*, 2011). In the sustainable lifestyle scenarios, increased home office, online services and e-commerce reduce mobility demand in 10%, affecting both fuel and public transportation.

Complementarily, D`AGOSTO *et al.* (2017 in LA ROVERE *et al.* (2017)) estimate that favoured non-motorized transportation (e.g. walk or bike for short distances) may contribute to decreasing demand in 2.9% for private[59] and 4.4% for public transportation. Fewer business air trips are needed, and demand for trips with leisure purposes also decrease.

FAÇANHA *et al.* (2012) estimate that, in Brazil, 9.2% of LDV transportation can be shifted to buses and 5.2% to rail by 2030. We assume this trend corresponds to a 13% shift towards buses and 7% towards subways and urban trains in 2050.

The above described trends, combined with the used of carpooling and car sharing services, lead to lower car ownership rates. We assume this induces a 40% reduction in private cars purchases, in line with existing literature (see (BLOK *et al.*, 2016; FIRNKORN; MÜLLER, 2011; GIROD; DE HAAN, 2009; GOVERNMENT OF CANADA, 2006; METRO VANCOUVER, 2014; NAMAZU; DOWLATABADI, 2015; SHAHEEN; COHEN, 2013))[60].

In the remaining passenger momentum met by private transportation, flex-fuel vehicles, both internal combustion and hybrid ones, are increasingly fueled with ethanol instead of gasoline, a shift estimated at 45%.

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[59] These figures are conservative compared to FAÇANHA *et al.* (2012) estimates. They consider that 4% of light-duty activity could shift to non-motorized transportation in 2030, in a global average.

[60] In the United States, rapid adoption of car sharing is estimated to reduce annual new car sales by nearly 50% among adhering users (BLOK *et al.*, 2016). GIROD AND DE HAAN (2009) find that Swiss households with the lowest GHG emissions per capita owned 24% less private cars that the national average.

A minor variation in electricity demand is also considered, regarding the effect on electric vehicles, which account for a small share of LDV fleet in 2050, around 9.6% (D´AGOSTO *et al.*, 2017 in LA ROVERE *et al.* (2017)).

Food

Based on PERNOLLET *et al.* (2017), we assume that households shift to diets with reduced meat consumption, replacing animal protein for vegetables, fruits and cereals. Pursuit of healthier diets also leads to a decreased consumption of beverages and industrialized products in general (see Table 5.13). For such simulation, we used the POF2008-2009 special publication on food, which provides both physical intake (grams per day) and monetary expenditure data (IBGE, 2011).

In line with UN's Sustainable Development Goals, which aim to halve per capita food waste at the retail and consumer levels by 2030[61], we assume that increased awareness lead to a 5% reduction in waste generation. The composition of each diet per category is shown in the table below, while Table AII.5 in Annex II depicts the variation on physical intake per category.

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[61] SDG12: "Ensure sustainable consumption and production patterns" includes amongst its objectives to "halve per capita global food waste at the retail and consumer level, and reduce food losses along production and supply chains by 2030" (UN, 2015b). Available at:

http://www.un.org/sustainabledevelopment/sustainable-consumption-production/

Table 5.13 - Composition for average and healthy diets by product category (%) in PERNOLLET *et al.* (2017)

	Average	Healthy
Bread & cereals	14.4%	20.5%
Fruits & Vegetables	35.0%	48.3%
Poultry	2.2%	0.4%
Other meats	6.1%	1.7%
Beef	3.3%	1.2%
Fish & Seafood	2.1%	1.8%
Animal products	10.7%	9.6%
Oils and fats	1.1%	1.3%
Beverages[62]	n.d.	n.d.
Other foods	25.2%	15.2%

Source: Author`s elaboration based on PERNOLLET *et al.* (2017)

Household appliances, furniture, personal belongings:

Expanding the product-life of consumer goods is considered underlying when linking material-efficiency and reduced environmental impact (BLOK *et al.*, 2016; HESTIN *et al.*, 2016; WIJKMAN; SKÅNBERG, 2015). In this scenario, households adopt 'reduce, reuse and recycle' policies through extended lifespan, `do it yourself`, second-hand purchase, sharing economy (renting, lending and borrowing instead of buying).

Using existing data for Swiss households surveys between 2000 and 2003, (GIROD; DE HAAN, 2009) find that, for a given level of total expenditure and similar household characteristics, the lowest GHG emissions per capita group spend 28% less than the average on electronic equipments and 15.5% less on goods in general (clothing, footwear, furniture, etc.). We use these numbers as a benchmark to our assumptions, in which a 30% reduction on demand for goods in simulated, considering that sharing and reusing possibilities, as well as awareness in general, are much broader in 2050. This is not valid, however, to goods used in household maintenance, for which we assume a 10% increase in demand, needed for repairing and DIY, for example.

[62] PERNOLLET *et al.* (2017) do not take into account the consumption of beverages. A 20% reduction in consumption was arbitrarily defined for this category.

Additional literature qualitatively supporting lifestyle changes assumptions can be found in ITDP (2014), KRISTÖM AND KIRAN (2014), MILLOCK (2014), EHREKE *et al.* (2014), PALATNIK (2014), NAUGES (2014), ADEME (2013, 2014, 2015), WEISS AND PEREIRA JR (2017a in LA ROVERE *et al.* (2017)), GREENPEACE (2016), among others. Ethnographic research performed by BARBOSA AND VELOSO (BARBOSA; VELOSO, 2014) support qualitatively assumptions on household behaviour. The authors point out various unsustainable habits within Brazilian households with different profiles. Namely, they identify wasteful habits regarding cooking, eating, cleaning and the use of appliances. Thriftless behaviour such as wasting food and leaving appliances unnecessarily on is often related to a 'sign of distinction', that is, affirming oneself socially by indulging in a middle-class consumption pattern.

5.3.2.2 Lower GHG emissions lifestyles scenario with increased trade activity (LES-Tr)

This scenario is similar to the previous one regarding household behaviour. In this case, reduced internal demand is partially offset by higher exports[63] in the oil, liquid fuels, agriculture and industrial sectors, which are internationally competitive.

The increase in production to meet the needs of a growing population with changing dietary preferences will require a global expansion of cultured land, and Brazil is expected to act as one of the major suppliers of agricultural commodities (FAO, 2011; OECD, 2012).

Increasing crude oil and oil products exports is plausible even in a scenario in which global climate efforts are put in place. As stated in section 2.5, the greatest share of world population growth occurs in Asian and African countries, which are expected to account for 7.8 billion people in 2050 (80% of world population) (UN, 2017). They

[63] The exogenous parameter δ_{Xi} (see equation 64 in Annex I) is altered in order to account for increased exports.

depart from much lower current living standards compared to Brazil. For instance, in India, 21% of the population (almost 270 million people) did not have access to electricity in 2014 (WORLD BANK, 2018c, 2018d). With huge booming middle classes, energy demand shall grow at a much faster pace in Asia and Africa than in the rest of the world. At the same time, some of them like China and India must do so by shifting from coal-based energy matrices to cleaner ones, and oil is expected to act as a transition fuel, as they embark in a 'peak-plateau-and-decline' emissions trajectory. Recent global scenarios exercises state that global oil demand is not expected to decrease in the coming decades, even in a climate-constrained world (JAKOB; HILAIRE, 2015; MCGLADE; EKINS, 2015). Brazilian oil exports are expected to increase with growing feasibility of exploiting pre-salt reserves (LEFÈVRE *et al.*, 2018; LUCENA *et al.*, 2016).

5.3.2.3 Varying levels of action towards lower emitting consumption across income classes

As discussed in section 2.4, income and environmental awareness usually keep a positive correlation[64]. In the sustainable lifestyle scenarios, it was assumed that the degree of action towards an environmentally friendly behaviour increases with the level of income. In other words, richer households engage proportionally more than poorer ones. This is due not only to the varying perception, but also because their absolute level of consumption is higher. There are greater possibilities for them to reduce consumption of resource-intensive goods and services without jeopardizing well-being than for low-income households, which are closer to basic needs attendance levels.

The AKATU Sustainable Society Index was used to mark this assumption (INSTITUTO AKATU, 2013). It uses a normalized index to assess consumer behaviour and aspirations regarding sustainable practices. It is computed for four different social

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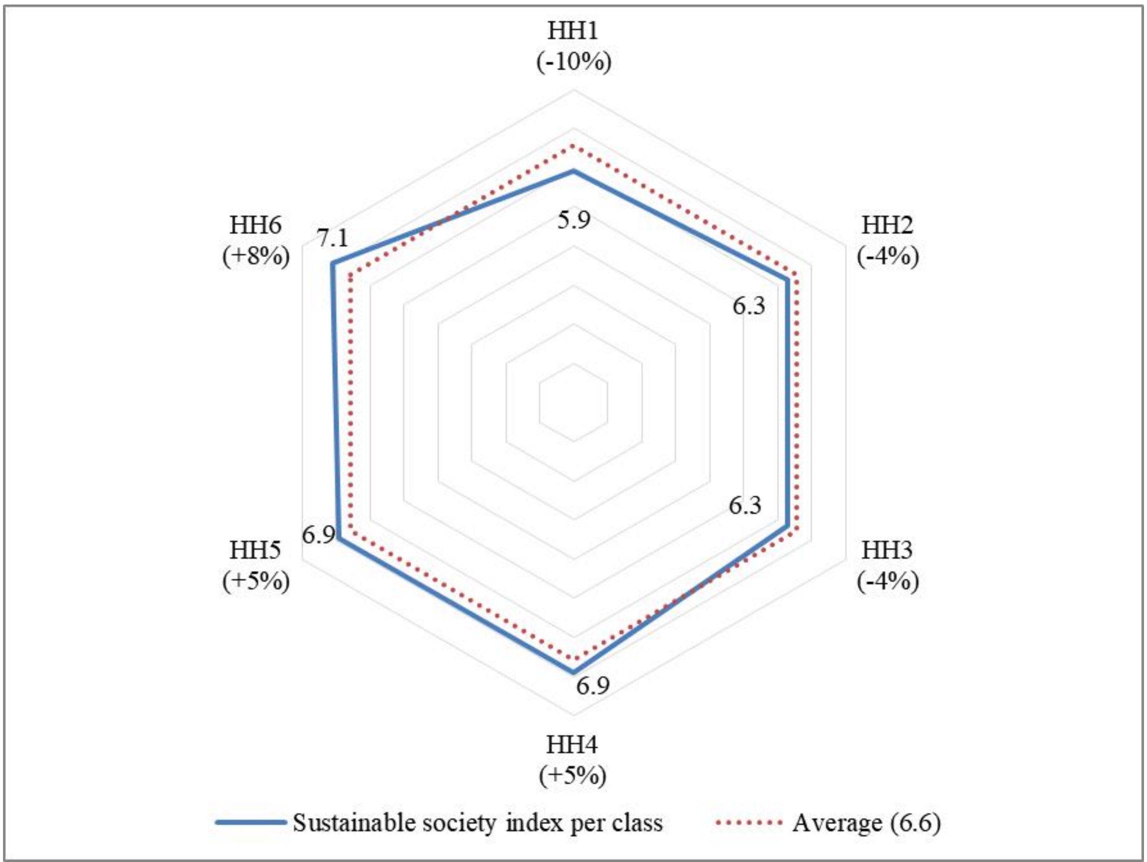
[64] BARBOSA AND VELOSO (BARBOSA; VELOSO, 2014) identify a positive relation between income level and acquaintance with the broader concept of 'sustainability' in a qualitative research within Brazilian households.

classes, from A to D, being the former the richest and the latter the poorest one. It was assumed here that the first income class (HH1) corresponds to class D, the next (HH2 and HH3) to class C, while classes HH4 and HH5 belong to class B and HH6 to class A. The average sustainable society score and relative variation to national average for the six income classes are depicted in Figure 5.11. A positive figure indicates a willingness to shift consumption towards more sustainable practices, while negative figures indicate a difficulty to do so.

Figure 5.11 - Sustainable society index per income class



Source: Author`s elaboration based on INSTITUTO AKATU (2013)

The sustainable society index for the first three income classes is lower than national average and higher for the top three ones. The deviation to the average degree of action for each of the behavioural changes depicted in Table 5.14 is set accordingly. The following section explores such dynamics in more detail.

5.3.2.4 Final consumption structure per income class

In order to simulate consumption shifts in Imaclim-S BR, it is initially necessary to identify to what extent they alter the final consumption of various COICOP categories for each income class, and what this represents in the model's 19 aggregate sectors, in terms of percentage variation of final demand. A 'bridge table' is used with such purpose, as proposed in MONGELLI *et al.* (2010). It enables the outlining of 'many-to-one' relationships between Imaclim-S BR and POF categories. See Annex II for clarification.

The remaining budget is shifted to the 'Composite' sector, to which belong activities related to well-being services, culture, sports, recreation, health and education. This is valid even if the household group savings rate is negative[65]: it assures that households` total consumption budget does not change (consequently total household welfare levels are kept, if we consider consumption as a proxy for it).

[65] This does not mean that savings rates do not vary along the assessed period, on the contrary. In base year, lower income deciles' expenditures surpass enormously their total income, leading to negative savings rates (-146% for the lowest decile). This is mainly caused by the underreporting of income, related to informal activities, for example, and reveals that household income must be further explored. In the reference scenario, education and labour policies that contribute to a better income distribution help households adjusting their savings.

Table 5.14 - Cumulate effect of behaviour shifts in household consumption relative to reference scenario, per class (%)

	Shift to public transportation	**Shift to ethanol**	**Non-motorized transportation**	**Reduced mobility demand**	**Residential energy savings**	**Reduced animal protein demand**	**Lower car ownership rates**	**Reduced overall demand for consumer goods**	**Cumulate effect**	**HH1**	**HH2**	**HH3**	**HH4**	**HH5**	**HH6**
Biomass															
Ethanol	-20%	45%	-2.9%	-10%					**1.5%**	1.3%	1.4%	1.4%	1.5%	1.5%	1.6%
Fuel wood									**0%**	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Charcoal									**0%**	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Coal									**n/a**	n/a	n/a	n/a	n/a	n/a	n/a
Oil									**n/a**	n/a	n/a	n/a	n/a	n/a	n/a
Natural gas					-10%				**-10%**	-9.0%	-9.6%	-9.6%	-10.5%	-10.5%	-10.8%
Oil products															
Gasoline	-20%	-45%	-2.9%	-10%					**-62%**	-55.4%	-59.2%	-59.2%	-64.8%	-64.8%	-66.7%
Liquefied petroleum gas					-10%				**-10%**	-9.0%	-9.6%	-9.6%	-10.5%	-10.5%	-10.8%
Electricity	-0.8%		-0.1%		-14.3%				**-15%**	-13.5%	-14.4%	-14.4%	-15.8%	-15.8%	-16.3%
Public Transportation															
Road	13%		-4.40%	-10%					**-3%**	-2.7%	-2.8%	-2.8%	-3.1%	-3.1%	-3.2%
Rail	7%			-10%					**-4%**	-3.1%	-3.4%	-3.4%	-3.7%	-3.7%	-3.8%
Water				-10%					**-10%**	-9.0%	-9.6%	-9.6%	-10.5%	-10.5%	-10.8%
Air				-10%					**-10%**	-9.0%	-9.6%	-9.6%	-10.5%	-10.5%	-10.8%
Livestock									**0%**	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

	Shift to public transportation	Shift to ethanol	Non-motorized transportation	Reduced mobility demand	Residential energy savings	Reduced animal protein demand	Lower car ownership rates	Reduced overall demand for consumer goods	Cumulate effect	HH1	HH2	HH3	HH4	HH5	HH6
Agriculture and agroindustry[66]															
Bread & cereals						58%		-5%	**50%**	45.4%	48.4%	48.4%	53.0%	53.0%	54.6%
Fruits & Vegetables						54%		-5%	**46%**	41.5%	44.3%	44.3%	48.5%	48.5%	50.0%
Poultry						-79%		-5%	**-80%**	-72.1%	-77.0%	-77.0%	-84.3%	-84.3%	-86.7%
Other meats						-68%		-5%	**-70%**	-62.5%	-66.7%	-66.7%	-73.1%	-73.1%	-75.2%
Beef						-61%		-5%	**-63%**	-56.2%	-60.0%	-60.0%	-65.7%	-65.7%	-67.6%

[66] Animal products are comprised in Agriculture and Agroindustry sector, a miscellaneous sector that includes all food products, with varying carbon intensities. Estimating a reduction in animal protein demand simply by altering households final demand in the aggregate sector does not capture the reducing emissions effect of such measure. Moreover, the demand for non-animal products increases simultaneously, also contributing to lowering the sector´s carbon intensity.

For this simulation in particular, a side analysis was required. An input-output assessment using 2005 National Accounts (IBGE, 2007) was performed in order to estimate the effects of changing households final demand levels in technical coefficients. Reduced demand for animal products leads to a 26% reduction in the technical coefficient between Agriculture and Agroindustry and Livestock (that is, how much the former demands from the latter in intermediary consumption). Analogously, since the demand for agricultural products is higher, the Agriculture and Agroindustry purchases more from itself. The technical coefficient variation was estimated at a 10% increase.

In the Sustainable Consumption with Compensation scenario, it was arbitrarily defined that the variation is halved, that is, a 13% reduction in the Agriculture and Agroindustry – Livestock technical coefficient and a 5% increase in the intraindustrial one. These results were explicitly informed to Imaclim-S BR according to the simulated scenario.

	Shift to public transportation	Shift to ethanol	Non-motorized transportation	Reduced mobility demand	Residential energy savings	Reduced animal protein demand	Lower car ownership rates	Reduced overall demand for consumer goods	Cumulate effect	HH1	HH2	HH3	HH4	HH5	HH6
Fish & Seafood						-1%		-5%	**-6%**	-5.5%	-5.8%	-5.8%	-6.4%	-6.4%	-6.6%
Animal products						0%		-5%	**-5%**	-4.5%	-4.8%	-4.8%	-5.3%	-5.3%	-5.4%
Oils and fats						39%		-5%	**32%**	28.8%	30.8%	30.8%	33.7%	33.7%	34.7%
Beverages						-20%		-5%	**-24%**	-21.6%	-23.0%	-23.0%	-25.2%	-25.2%	-25.9%
Other foods						-33%		-5%	**-36%**	-32.4%	-34.6%	-34.6%	-37.9%	-37.9%	-39.0%
Energy-intensive industry															
Goods for household maintenance								10%	**10%**	9.0%	9.6%	9.6%	10.5%	10.5%	10.8%
Hygiene items								-30%	**-30%**	-27.0%	-28.8%	-28.8%	-31.5%	-31.5%	-32.4%
Non energy-intensive industry															
Household appliances								-30%	**-30%**	-27.0%	-28.8%	-28.8%	-31.5%	-31.5%	-32.4%
Furniture and furnishing								-30%	**-30%**	-27.0%	-28.8%	-28.8%	-31.5%	-31.5%	-32.4%
Clothing, footwear, personal effects								-30%	**-30%**	-27.0%	-28.8%	-28.8%	-31.5%	-31.5%	-32.4%
Purchase of individual vehicle							-40%		**-40%**	-35.9%	-38.4%	-38.4%	-42.0%	-42.0%	-43.2%
Telephone, audiovisual, computer								-30%	**-30%**	-27.0%	-28.8%	-28.8%	-31.5%	-31.5%	-32.4%

	Shift to public transportation	Shift to ethanol	Non-motorized transportation	Reduced mobility demand	Residential energy savings	Reduced animal protein demand	Lower car ownership rates	Reduced overall demand for consumer goods	Cumulate effect	HH1	HH2	HH3	HH4	HH5	HH6
Audiovisual and information processing equipment								-30%	**-30%**	-27.0%	-28.8%	-28.8%	-31.5%	-31.5%	-32.4%
Other recreational items and equipment								-30%	**-30%**	-27.0%	-28.8%	-28.8%	-31.5%	-31.5%	-32.4%
<u>Services</u>															
Feeding out of home									**n/a**	n/a	n/a	n/a	n/a	n/a	n/a
Actual rentals for housing									**n/a**	n/a	n/a	n/a	n/a	n/a	n/a
Loan payments for dwelling									**n/a**	n/a	n/a	n/a	n/a	n/a	n/a
Water supply and miscellaneous services relating to the dwelling									**n/a**	n/a	n/a	n/a	n/a	n/a	n/a
Services for household maintenance									**n/a**	n/a	n/a	n/a	n/a	n/a	n/a
Personal care services									n/a	n/a	n/a	n/a	n/a	n/a	n/a
Individual vehicle maintenance and others services									**n/a**	n/a	n/a	n/a	n/a	n/a	n/a

	Shift to public transportation	Shift to ethanol	Non-motorized transportation	Reduced mobility demand	Residential energy savings	Reduced animal protein demand	Lower car ownership rates	Reduced overall demand for consumer goods	Cumulate effect	HH1	HH2	HH3	HH4	HH5	HH6
Health services									**n/a**	n/a	n/a	n/a	n/a	n/a	n/a
Private health care									**n/a**	n/a	n/a	n/a	n/a	n/a	n/a
School fees for primary or secondary education									**n/a**	n/a	n/a	n/a	n/a	n/a	n/a
Telephone and postal services									**n/a**	n/a	n/a	n/a	n/a	n/a	n/a
Sports and culture (services)									**n/a**	n/a	n/a	n/a	n/a	n/a	n/a
Other expenses									**n/a**	n/a	n/a	n/a	n/a	n/a	n/a

Source: Author`s elaboration

The new consumption structure per class is presented in Table 5.15, compared with reference projection (repeated in Table 5.12 below for the sake of comparison). Households seek to meet their basic needs, spending less in all categories, except biomass, for it replaces fossil fuels in private transportation, and devoting the remaining budget to services, which accounts for more than 80% for the richest decile.

Table 5.12 (repeated) - Expenditures budget share per class in 2050 – REF (% of household consumption income)

	HH1	HH2	HH3	HH4	HH5	HH6
Biomass	1.7%	1.3%	1.1%	0.8%	0.6%	0.3%
Natural Gas	0.1%	0.1%	0.1%	0.1%	0.0%	0.0%
Oil products	2.4%	2.2%	2.3%	3.6%	4.1%	3.4%
Electricity	2.1%	1.9%	1.9%	1.9%	1.7%	1.1%
Public transportion	4.6%	4.1%	4.1%	4.1%	3.7%	2.3%
Livestock	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Agriculture and agroindustry	19.9%	16.9%	17.0%	11.9%	9.7%	4.6%
Energy intensive industry	6.4%	5.6%	5.6%	5.6%	4.7%	3.1%
Rest of Industry	13.8%	16.2%	16.2%	16.2%	16.9%	10.2%
Services	48.9%	51.7%	51.7%	55.7%	58.5%	75.0%
Total	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

Source: Author`s elaboration

Table 5.15 - Expenditures budget share per class in 2050 - LES and LES-Tr (% of household consumption income)

	HH1	HH2	HH3	HH4	HH5	HH6
Biomass	1.7%	1.3%	1.2%	0.9%	0.6%	0.3%
Natural Gas	0.1%	0.1%	0.1%	0.1%	0.0%	0.0%
Oil products	1.5%	1.2%	1.2%	1.6%	1.8%	1.4%
Electricity	1.8%	1.6%	1.6%	1.6%	1.4%	0.9%
Public transportation	4.5%	4.0%	4.0%	4.0%	3.5%	2.1%
Livestock	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Agriculture and agroindustry	19.0%	16.0%	15.8%	10.8%	8.7%	4.3%
Energy intensive industry	6.0%	5.3%	5.3%	5.3%	4.5%	3.0%
Rest of Industry	9.8%	11.1%	11.0%	10.4%	10.7%	6.3%
Services	55.6%	59.5%	59.9%	65.4%	68.7%	81.7%
Total	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

Source: Author`s elaboration

6 Results and discussion

This chapter presents the main results of scenarios simulations, split into macroeconomic results (section 6.1), household results (section 6.2) and greenhouse gases emissions (section 6.3). A general discussion comparing the findings with existing literature is then performed (sections 6.4 and 6.5), followed by suggestions for further research (section 6.6).

6.1 Macroeconomic results

6.1.1 GDP, sectoral output and employment

The main macroeconomic results for the three scenarios up to 2050 are presented in Table 6.1. In Table 6.2 depicting results per sector, output for energy sectors is expressed in tons of oil equivalents, public transportation in pass.km and other goods and services are presented in 'quasi-quantities', for which monetary values in constant prices for 2005 are considered a good proxy (see footnote 22 for explanation).

In the reference scenario, the economy evolves at a 2.73% annual growth rate on average, compatible with assumptions described in the previous chapter. Reduced domestic demand for resource-intensive products as in scenario LES does not jeopardize GDP, leading to a minor reduction of growth rates and a real GDP 2.6% lower in 2050 compared to baseline. In contrast, total job creation decreases at a much lesser extent (-0.03%), keeping unemployment rates virtually unchanged. This is due to an activity shift from sectors that are not labour-intensive such as fossil energy to services (Source: Author`s elaboration

Table 6.3). This also explains the reason total wages decrease less than GDP (-1.5%). In scenario LES-Tr, the GDP level is similar to the reference case, but with a different economy structure regarding both sectoral production and final demand. As in LES, household demand shifts towards services. However, reduced domestic demand for crude oil, its derivates and industrial goods, including agroindustry, is partially offset by higher exports, leading to the same total activity level. Job creation is similar to the reference case but wage payments are higher. Such interactions will be further explored in the following sections.

Table 6.1 - Macroeconomic indicators[67]

	2005	2050		
	Base year	**REF**	**LES**	**LES-Tr**
Population (millions)	185	226	226	226
Real GDP (trillion R$2005)	2.14	7.21	7.02	7.21
Variation relative to REF (%)	-	-	-2.6%	0.0%
Average GDP annual growth (%)	-	2.73%	2.67%	2.73%
GDP per capita (thousand R$2005)	11.57	31.86	31.02	31.86
Total real wages (millions R$2005)	805,150	1,063,092	1,047,676	1,099,437
Variation relative to REF (%)	-	-	-1.5%	3.4%
Number of jobs (thousands)	91,212	112,565	112,555	112,596
Variation relative to REF (%)	-	-	0.0%	0.0%
Unemployment rate (%)	8.56%	7.45%	7.46%	7.42%

Source: Author`s elaboration

[67] Exchange rate in 2005: 2.43 R$/US$

Table 6.2 - Sectoral output and variation from base year (%)

	2005		2050	
	Base year	REF	LES	LES-Tr
Biomass (10^3 toe)	80,940	197,956	190,081	191,114
Coal (10^3 toe)	2,388	9,064	8,003	7,329
Oil (10^3 toe)	84,186	225,895	190,020	191,928
Natural Gas (10^3 toe)	16,054	61,400	53,206	51,401
Oil products (10^3 toe)	93,903	201,375	161,784	164,399
Electricity (10^3 toe)	34,653	120,668	113,405	113,568
Public transportation (10^6 pass.km)	1,746,570	5,530,576	5,334,016	5,374,879
Livestock (10^6 R$2005)	14,399	43,726	35,188	38,663
Agriculture and agroindustry (10^6 R$2005)	418,710	1,177,147	1,105,082	1,110,018
Energy intensive industry (10^6 R$2005)	343,028	1,043,295	964,871	1,006,919
Rest of Industry (10^6 R$2005)	733,908	2,391,880	2,124,639	2,112,871
Services (10^6 R$2005)	1,738,809	5,923,207	6,258,599	6,251,424
Biomass	-	145%	135%	136%
Coal	-	280%	235%	207%
Oil	-	168%	126%	128%
Natural Gas	-	282%	231%	220%
Oil products	-	114%	72%	75%
Electricity	-	248%	227%	228%
Public transportation	-	217%	205%	208%
Livestock	-	204%	144%	169%
Agriculture and agroindustry	-	181%	164%	165%
Energy intensive industry	-	204%	181%	194%
Rest of Industry	-	226%	189%	188%
Services	-	241%	260%	260%

Source: Author`s elaboration

Table 6.3 - Jobs per sector (thousand) and share on total jobs (%)

	2005		2050	
	Base year	REF	LES	LES-Tr
Biomass	2,329	2,202	2,100	2,111
Coal	8	11	10	9
Oil	38	39	33	33
Natural Gas	5	7	6	6
Oil products	143	118	95	96
Electricity	233	312	293	293
Public transportation	3,858	4,691	4,524	4,558
Livestock	1,000	1,165	938	1,031
Agriculture and agroindustry	18,000	19,393	18,240	18,322
Energy intensive industry	1,619	1,891	1,748	1,825
Rest of Industry	14,007	17,455	15,569	15,482
Services	49,973	65,283	69,000	68,830
Total	**91,212**	**112,565**	**112,555**	**112,596**
Biomass	2.6%	2.0%	1.9%	1.9%
Coal	0.0%	0.0%	0.0%	0.0%
Oil	0.0%	0.0%	0.0%	0.0%
Natural Gas	0.0%	0.0%	0.0%	0.0%
Oil products	0.2%	0.1%	0.1%	0.1%
Electricity	0.3%	0.3%	0.3%	0.3%
Public transportation	4.2%	4.2%	4.0%	4.0%
Livestock	1.1%	1.0%	0.8%	0.9%
Agriculture and agroindustry	19.7%	17.2%	16.2%	16.3%
Energy intensive industry	1.8%	1.7%	1.6%	1.6%
Rest of Industry	15.4%	15.5%	13.8%	13.8%
Services	54.8%	58.0%	61.3%	61.1%
Total	**100%**	**100%**	**100%**	**100%**

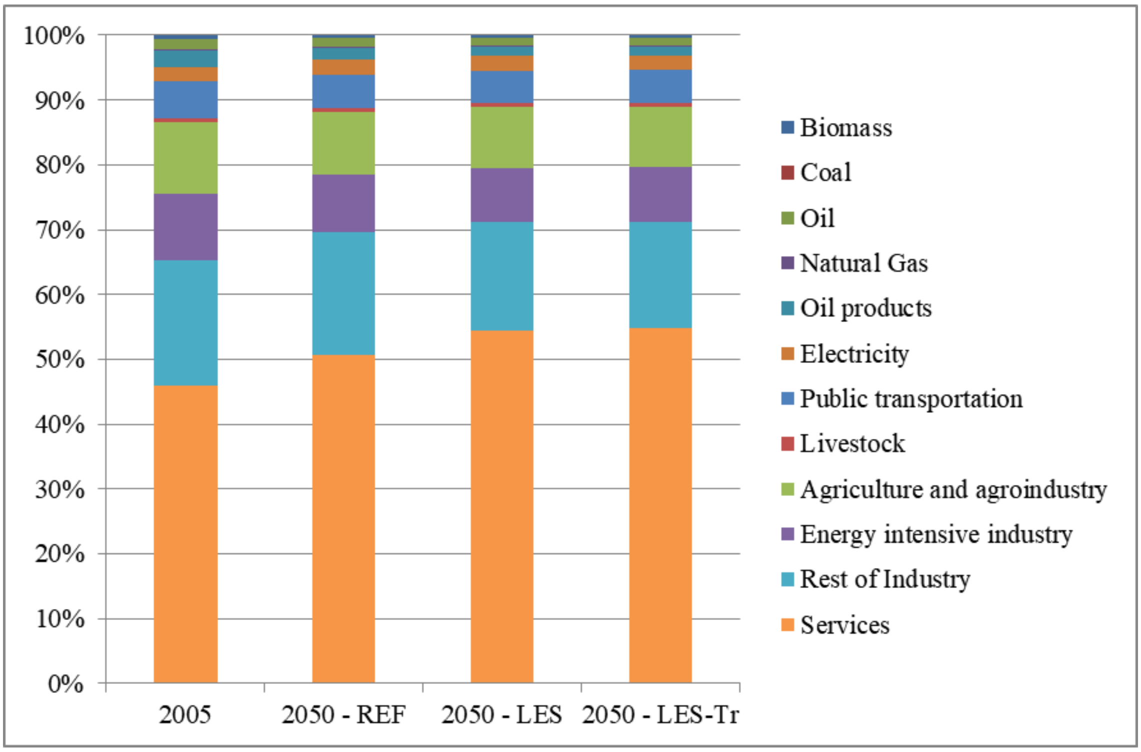
Source: Author`s elaboration

6.1.2 Wage levels and prices

Up to 2050, economic structure shifts towards services, the sole sector, together with Electricity, for which the share in total production increases in the reference case. While these two sectors generally pay above the average wages (Figure 6.2) sectors with lower than average wage levels (Biomass, Agriculture and Cattle) reduce their share in output and jobs (hence in wage payment)[68]. In REF, the increase in labour costs pushes the consumer price index up, at 6.2%.

In the lifestyles pathways, with the composite sector accounting for almost 70% of total wages (and average wage 13% higher than national standards), the impact on prices is even stronger, especially in LES-Tr, with higher activity also in other sectors with high wage levels such as Oil, Transport and Energy-intensive industry.

Figure 6.1 - Share in total production (%)



Source: Author`s elaboration

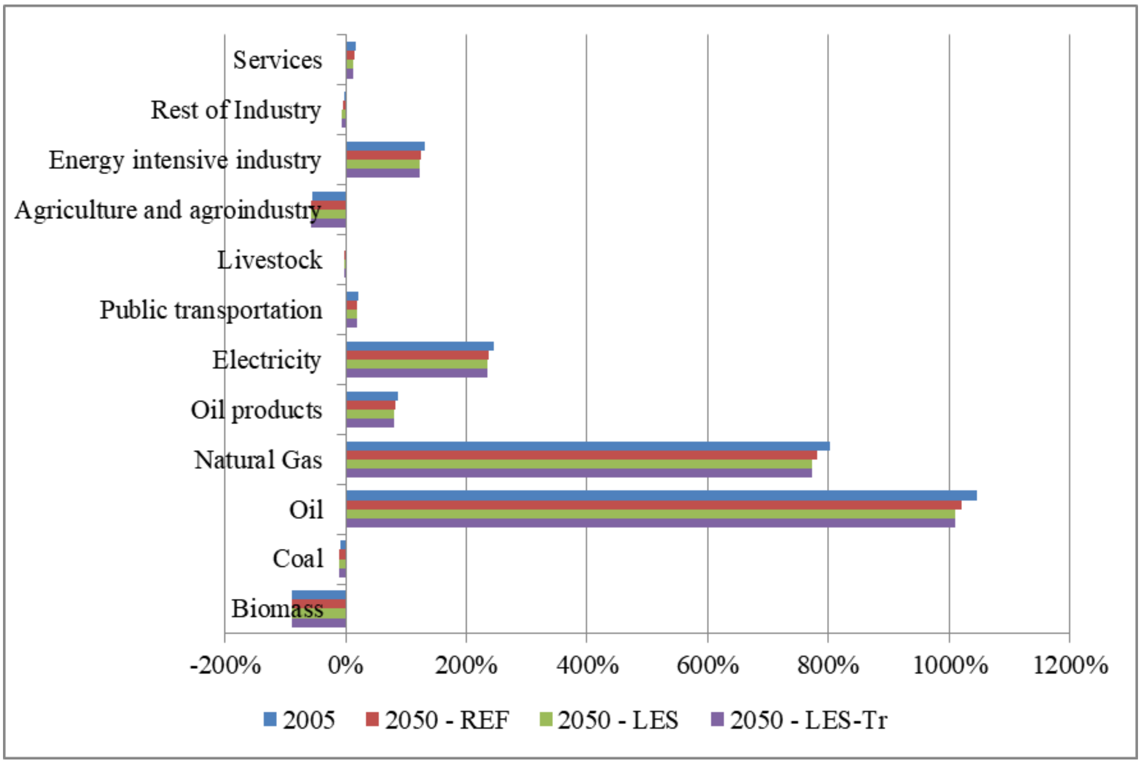
[68] Nominal and real wages and consumer price variations per sector can be found in Annex IV - Detailed Numerical Results.

Table 6.4 - Average wages and consumer price index

	2005		2050	
	Base year	REF	LES	LES-Tr
Average nominal wage (thousand R$2005)	8.8	10.0	10.7	12.8
Variation relative to 2005 (%)	-	14%	21%	45%
Average real wage (thousand R$2005)	8.8	9.4	9.3	9.8
Variation relative to 2005 (%)	-	7%	5%	11%
Consumer price index (2005=1)	1.00	1.06	1.15	1.32

Source: Author`s elaboration

Figure 6.2 - Wages per sector - Deviation from average domestic wage level (%)



Source: Author`s elaboration

Table 6.5 - Share in total wages per sector (%)

	2005	2050		
	Base year	REF	LES	LES-Tr
Biomass	0.3%	0.2%	0.2%	0.2%
Coal	0.0%	0.0%	0.0%	0.0%
Oil	0.5%	0.4%	0.3%	0.3%
Natural Gas	0.0%	0.1%	0.0%	0.0%
Oil products	0.3%	0.2%	0.2%	0.2%
Electricity	0.9%	0.9%	0.9%	0.9%
Public transportation	5.2%	5.0%	4.7%	4.8%
Livestock	1.1%	1.0%	0.8%	0.9%
Agriculture and agroindustry	8.6%	7.4%	6.9%	6.9%
Energy intensive industry	4.1%	3.8%	3.5%	3.6%
Rest of Industry	14.9%	14.8%	13.0%	13.0%
Services	64.1%	66.3%	69.5%	69.2%
Total	**100%**	**100%**	**100%**	**100%**

Source: Author`s elaboration

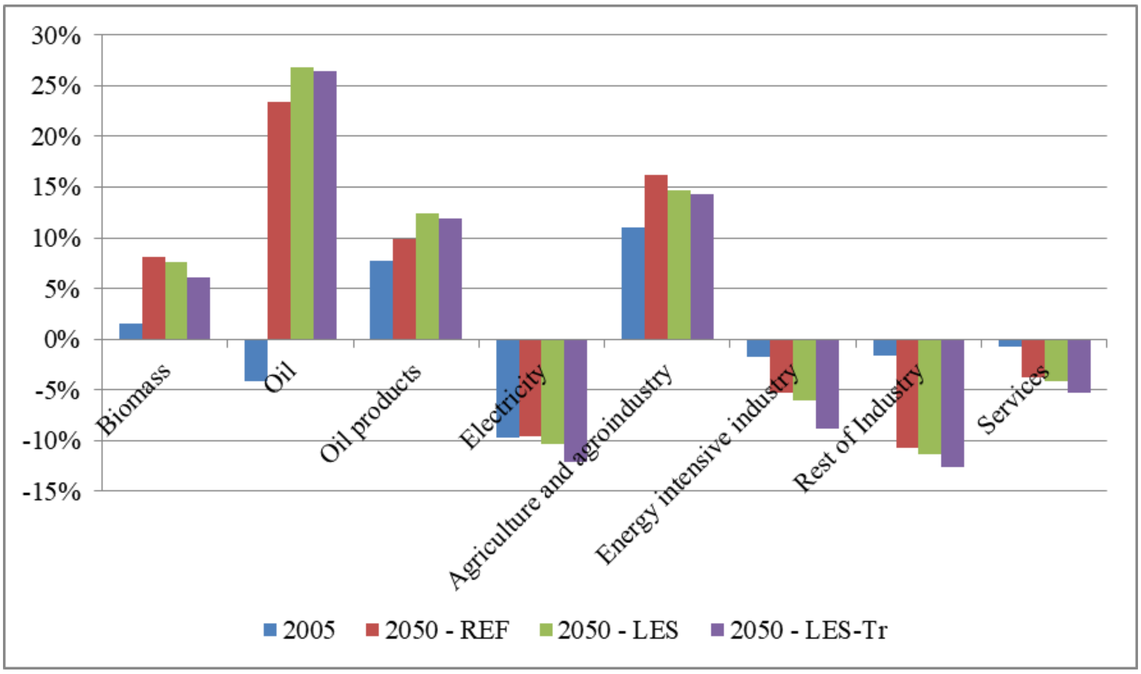
Despite significant variations in nominal wages in all scenarios, they have little impact on unemployment, for the wage curve is sensitive to real labour costs, with limited flexibility. In addition, there is also little flexibility for sectors to replace production factors, given an increase in costs, as explained in section 4.2.5.3. This is evidenced by the minor differences in labour and capital intensity variations relative to base-year across the three scenarios, depicted in Table AIV.3 in Annex IV.

6.1.3 Trade balance and investment rates

Source: Author`s elaboration

Table 6.3 presents the net exports to GDP ratio for sectors with high international trade activity. The Livestock and Public Transportation sectors are not included due to insignificant trade levels, while Coal and Natural gas sectors are not included for the sake of visualization[69].

Figure 6.3 - Net exports to sectoral GDP ratio (%)



Source: Author`s elaboration

Between 2005 and 2050, Brazil becomes a crude oil net exporter, as pre-salt layer reserves are exploited. Agricultural and industrial commodities exports also increase, reinforcing their importance to trade balance. Nonetheless, industrial sectors also require imported goods, and, in the aftermath, the trade balance to GDP ratio is lower in 2050 than in base year for all scenarios.

The impact of rising prices on trade is clear, for every sector (either a net importer or net exporter) is negatively affected by the higher price indexes in LES and LES-Tr. In LES-Tr, the oil, oil products, agriculture and industrial sectors seek to offset

[69] Coal and natural gas sectors exports levels are virtually nul, contrasted with high imports (between 360% and 485% of total output for Coal and between 43% and 53% of total output for Natural Gas, depending on the scenario).

their lower domestic demand by exporting more, but to a certain extent they are prevented by domestic high prices. In all sectors, imports increase substantially due to worsened terms of trade.

Table 6.6 - Investment rate and trade balance (% of GDP)

	2005		2050	
	Base year	REF	LES	LES-Tr
Investment rate (% of GDP)	16.0%	15.9%	15.7%	14.9%
Trade balance (% of GDP)	3.7%	1.8%	1.5%	1.6%

Source: Author`s elaboration

6.2 Households results

6.2.1 Income and Purchasing Power

Tables below show that, for middle deciles, gross income evolves somewhat like economic growth, whereas it grows at higher rates for lower income deciles and less than proportionally to the top ones. This is due to a more equitable distribution of labour income among classes and the extension of governmental cash transfer programmes for poor households. Growth rates for bottom deciles are consistent with a SSP exercise performed by ROZENBERG *et al.* (2014) using the global (recursive) version of Imaclim, according to which per capita income of the 20% poorest in a selection of developing countries increases up to six times 2010 levels[70].

Consumption income is inferred from gross disposable income by subtracting household savings. As part of the basic assumptions valid for all scenarios, lower income classes improve significantly their savings account status during the assessed period (see Table 6.9). Therefore, the poorer the class, the bigger is the gap between gross and consumption income evolution, the latter increasing less than the former.

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[70] See supplementary material available in:
http://www2.centre-cired.fr/IMG/pdf/scenario_mapping_supplementary_material_preprint.pdf

Table 6.7 - Real per capita gross disposable income (R$2005) and variation (%)

	2005	2050		
	Base year	**REF**	**LES**	**LES-Tr**
HH1	970	6,625	6,517	6,816
HH2	2,364	9,676	9,502	9,909
HH3	3,937	12,959	12,714	13,237
HH4	5,477	17,974	17,617	18,313
HH5	12,314	34,336	33,604	34,841
HH6	50,452	116,235	113,453	116,920
HH1	-	583%	572%	602%
HH2	-	309%	302%	319%
HH3	-	229%	223%	236%
HH4	-	228%	222%	234%
HH5	-	179%	173%	183%
HH6	-	130%	125%	132%

Source: Author`s elaboration

Table 6.8 - Real per capita consumption income (R$2005) and variation (%)

	2005		2050	
	Base year	**REF**	**LES**	**LES-Tr**
HH1	2,216	9,353	9,198	9,617
HH2	3,227	12,646	12,416	12,943
HH3	4,824	15,223	14,931	15,536
HH4	7,099	21,537	21,100	21,913
HH5	11,672	29,711	29,061	30,100
HH6	26,423	62,500	61,431	63,236
HH1	-	322%	315%	334%
HH2	-	292%	285%	301%
HH3	-	216%	210%	222%
HH4	-	203%	197%	209%
HH5	-	155%	149%	158%
HH6	-	137%	132%	139%

Source: Author`s elaboration

Table 6.9 - Savings rate (%)

	2005		2050	
	Base year	**REF**	**LES**	**LES-Tr**
HH1	-146%	-56%	-56%	-56%
HH2	-43%	-39%	-39%	-39%
HH3	-30%	-26%	-26%	-26%
HH4	-42%	-33%	-33%	-33%
HH5	-5%	4%	4%	4%
HH6	41%	41%	41%	41%

Source: Author`s elaboration

Improved income distribution is reflected in a lower Gini coefficient in all scenarios (Table 6.10). This index does not vary much across the different scenarios. It depends mainly on total gross household income, which in its turn, responds to employment (or more specifically, wages) and ultimately, to economic output. From 2005 to 2050, the Gini coefficient drops 18% in all scenarios. Final year levels are mostly determined by the ground assumption of more evenly allocated labour income, a reflection of implicitly assumed educational developments and lower levels of informality.

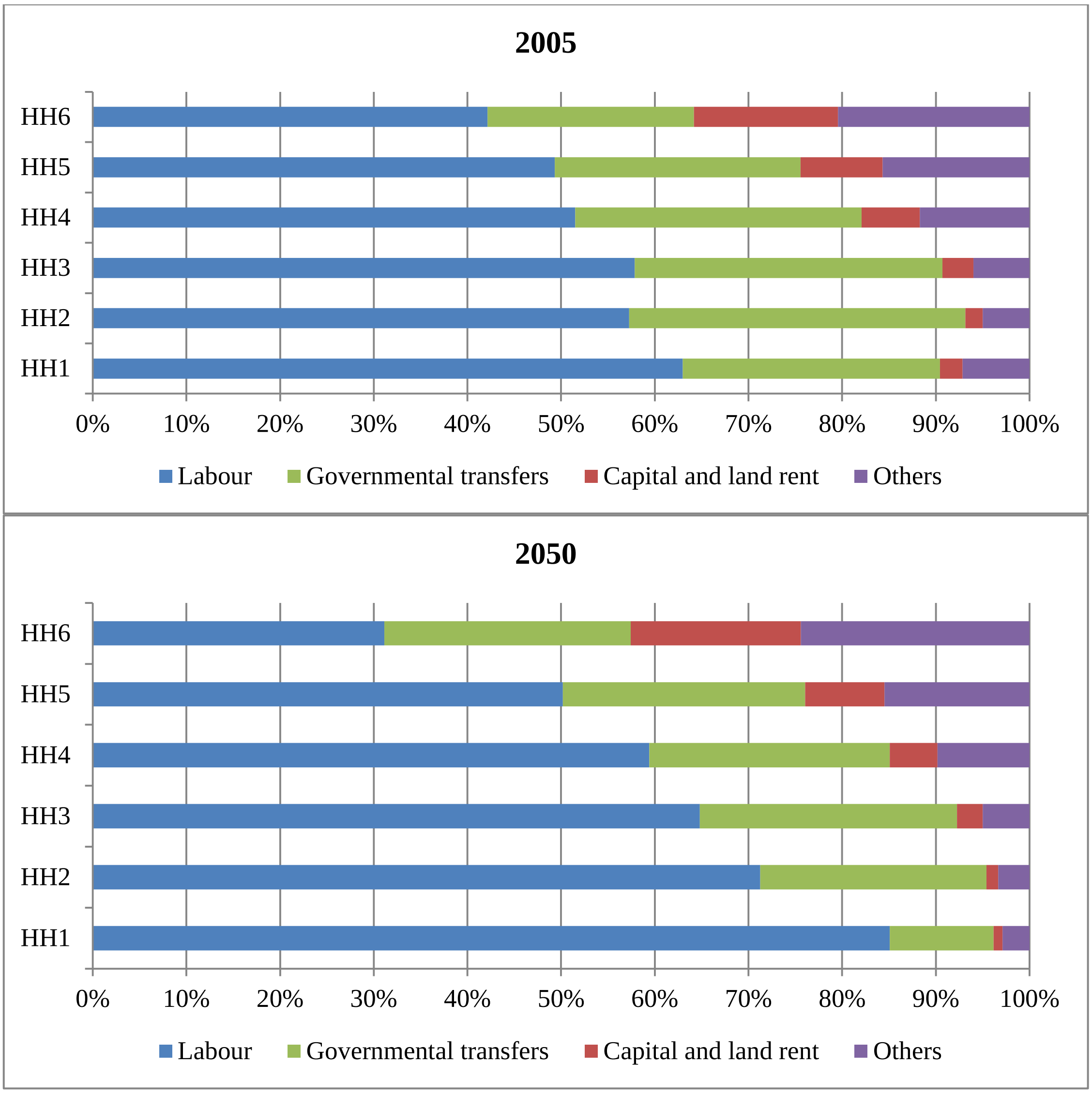
The share of labour income on total gross income increases for all classes (only slightly for HH5), except for HH6. The opposite occurs for governmental transfers and others (e.g. private pensions). This does not mean that for these sources increase more for the top class than for others. In fact, they vary according to GDP per capita, and base year distribution among classes is left unchanged, therefore the evolution is the same for all classes. The decreased share of labour income in HH6`s income formation (from 42% in 2005 to 31% in 2050) explains a more prominent participation of other sources (Figure 6.4).

Table 6.10 - Gini Coefficient

	2005		**2050**	
	Base year	**REF**	**LES**	**LES-Tr**
Gini coefficient	0.58	0.48	0.48	0.47

Source: Author`s elaboration

Figure 6.4 - Share on household gross income per source in 2005 and 2050 (%)



Source: Author`s elaboration

Since the way households allocate their household budget is defined by the level of income (see section 5.3.2.4), major prices variations across sectors in the three scenarios, explored in section 0 and Annex IV, affect them differently. A price index determined by the weighted share of each sector in the household consumption budget and the sectoral price variation in each one of the scenarios measures the evolution of the purchasing power per class (Table 6.11).

Table 6.11 - Income, price index per consumption basket and purchasing power variation relative to base year (2005=1)

	2005		2050	
	Base year	**REF**	**LES**	**LES-Tr**
		Income (2005=1)		
HH1	1.0	4.2	4.1	4.3
HH2	1.0	3.9	3.8	4.0
HH3	1.0	3.2	3.1	3.2
HH4	1.0	3.0	3.0	3.1
HH5	1.0	2.5	2.5	2.6
HH6	1.0	2.4	2.3	2.4
		Price index per weighted consumption basket (2005=1)		
HH1	1.0	0.99	1.05	1.18
HH2	1.0	1.00	1.05	1.17
HH3	1.0	1.00	1.05	1.17
HH4	1.0	1.00	1.05	1.17
HH5	1.0	1.00	1.05	1.18
HH6	1.0	0.99	1.04	1.16
		Purchasing power (2005=1)		
HH1	1.0	4.2	4.0	3.7
HH2	1.0	3.9	3.7	3.4
HH3	1.0	3.2	3.0	2.7
HH4	1.0	3.0	2.8	2.6
HH5	1.0	2.5	2.4	2.2
HH6	1.0	2.4	2.2	2.1

Source: Author`s elaboration

It is noteworthy that, despite major purchasing power gains compared to base year, higher consumer prices in both lifestyles scenarios lead to losses in purchasing power. The impact on purchasing power is heavier for lower income classes. As shown in Table AIV.4 in Annex IV, the impacts on nominal price variations in public transportation, electricity and food are among the highest, and these categories account for a higher share on poorer classes` budget than in richer ones. As a matter of fact, most of the purchasing power losses for top income classes come from services, for which prices soar as well (HH6 spends 75% of its budget on services in REF and 81.7% in LES and LES-Tr). However, all income classes spend a significant share of their budget on services in 2050 in all scenarios (nearly half of it or more), so the major differences in purchasing power deterioration across classes is indeed mostly explained by categories other than services. Yet, this does not prevent households from meeting their food and energy needs in any scenario, as further explored in the following section.

6.2.2 Consumption results

This section analyses the results for household per capita consumption up to 2050. Monetary expenditure for each category per class can be found in Annex IV (Tables AIV.5 to AI.12). In scenarios LES and LES-Tr, the budget share allocated to each sector per class does not change, but consumption levels in LES-Tr are slightly higher. This is the result of higher GDP growth, and its reflection on household income levels.

Direct energy consumption

Natural gas consumption increases substantially, above income levels, due to the expansion of the supply network in urban centers. It replaces LPG for cooking (and electricity for water heating), and contributes to decreasing households` carbon intensity of energy use in all scenarios, including the reference case.

Electricity consumption in the baseline evolves at a lesser pace, slightly above income growth for lower classes, along with higher ownership rates for domestic appliances. For upper classes it evolves way below income, as these households are close to saturation already today. A small part of the consumption increase is explained by the penetration of private electric vehicles.

In the lifestyles scenarios, residential energy savings achieved by reducing shower duration and temperatures, better planning cooking activities (and reducing food waste), turning appliances and bulbs off, avoiding stand-by mode, among others, lead to a reduction in both natural gas and electricity consumption.

Table 6.12 - Natural gas per capita consumption per class (toe), variation (%) and national average (m^3 per capita)

	2005	2050		
	Base year	REF	LES	LES-Tr
HH1	0.00	0.01	0.01	0.01
HH2	0.00	0.01	0.01	0.01
HH3	0.00	0.01	0.01	0.01
HH4	0.00	0.02	0.02	0.02
HH5	0.00	0.02	0.02	0.02
HH6	0.00	0.02	0.02	0.02
HH1	-	968%	893%	993%
HH2	-	636%	579%	644%
HH3	-	478%	432%	483%
HH4	-	804%	724%	801%
HH5	-	636%	570%	630%
HH6	-	523%	467%	514%
National average (m^3 per capita)	**1.2**	**16.6**	**15.2**	**16.6**

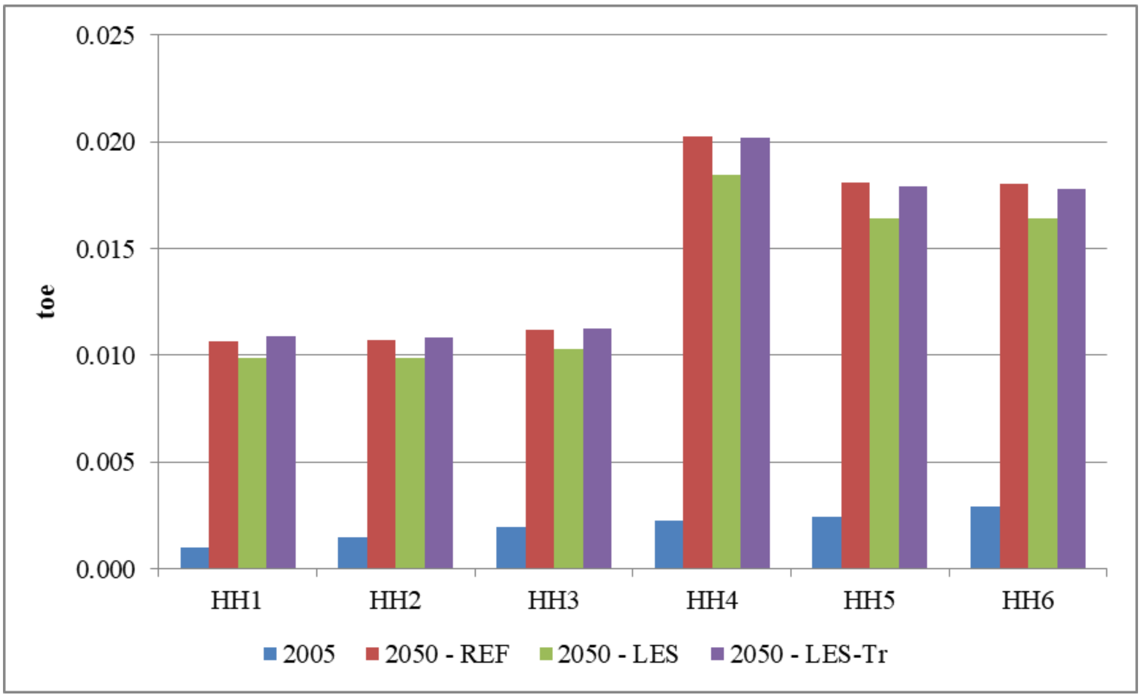
Source: Author`s elaboration

Table 6.13 - Electricity per capita consumption per class (toe), variation (%) and national average (kWh per capita)

	2005	2050		
	Base year	REF	LES	LES-Tr
HH1	0.01	0.05	0.05	0.05
HH2	0.02	0.07	0.06	0.06
HH3	0.03	0.08	0.07	0.07
HH4	0.04	0.11	0.10	0.10
HH5	0.06	0.14	0.12	0.12
HH6	0.10	0.19	0.16	0.17
HH1	-	389%	327%	353%
HH2	-	272%	221%	239%
HH3	-	164%	127%	140%
HH4	-	172%	130%	142%
HH5	-	128%	93%	103%
HH6	-	92%	63%	70%
National average (kWh per capita)	**449**	**1,158**	**987**	**1,039**

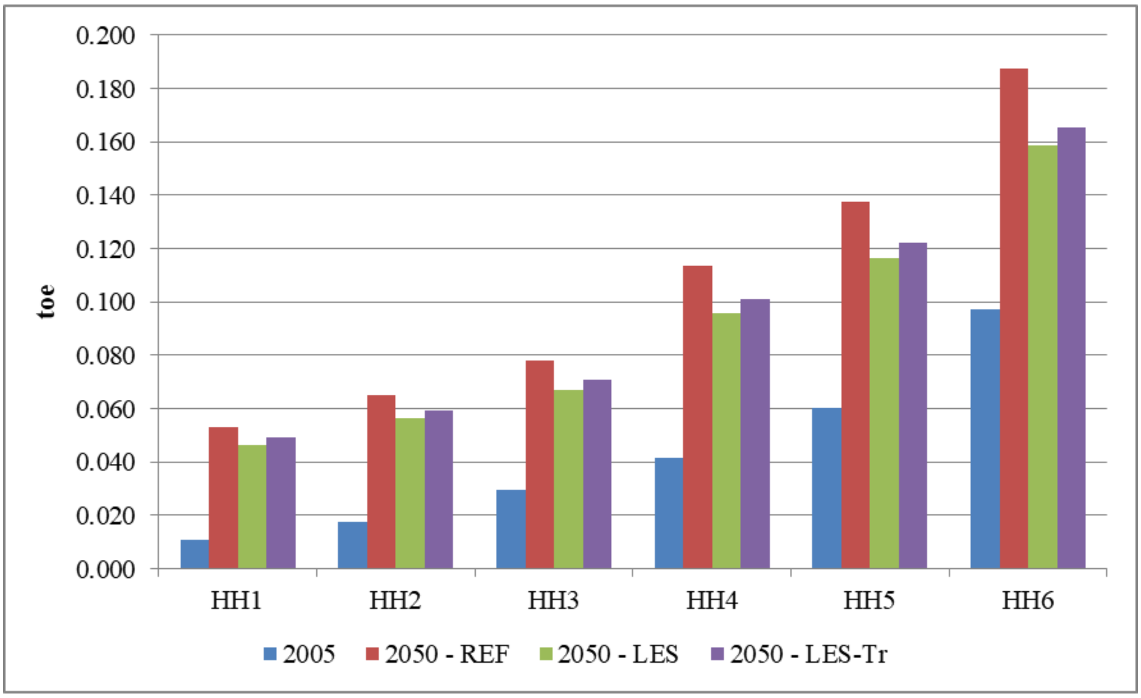
Source: Author`s elaboration

Figure 6.5 - Natural gas per capita consumption per class (toe)



Source: Author`s elaboration

Figure 6.6 - Electricity per capita consumption per class (toe)



Source: Author`s elaboration

Biomass consumption increases significantly in all scenarios, due to the expansion of biofuels in private transportation, namely sugar cane ethanol.

Simultaneously, households replace fuel wood and charcoal by LPG, and natural gas and, by 2050, traditional biomass for cooking represents a negligible share of total biomass consumption (Table 6.14).

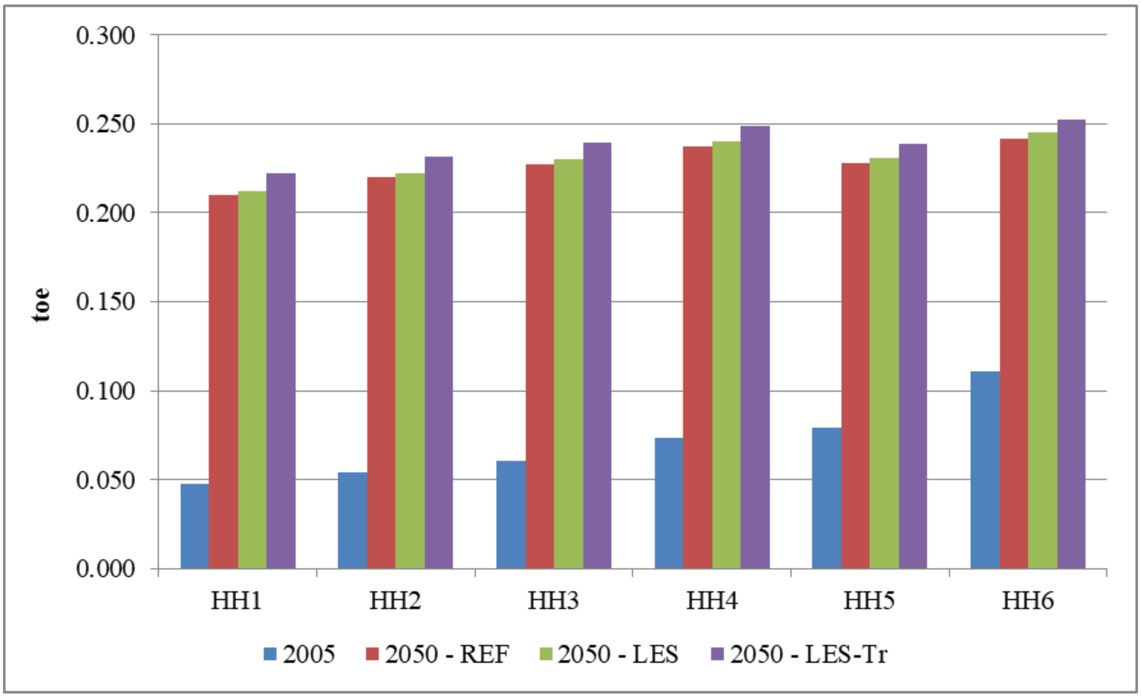
In the lifestyles scenarios, the reduced demand for private transportation pushes ethanol demand down, but households prioritize biofuels over fossil fuels for the remaining private trips. In the aftermath, demand levels are similar in all scenarios.

Table 6.14 - Biomass per capita consumption per class (toe), variation (%) and national average (commercial units per capita)

	2005		**2050**	
	Base year	**REF**	**LES**	**LES-Tr**
HH1	0.05	0.21	0.21	0.22
HH2	0.05	0.22	0.22	0.23
HH3	0.06	0.23	0.23	0.24
HH4	0.07	0.24	0.24	0.25
HH5	0.08	0.23	0.23	0.24
HH6	0.11	0.24	0.25	0.25
HH1	-	343%	347%	368%
HH2	-	306%	310%	328%
HH3	-	274%	278%	293%
HH4	-	224%	228%	240%
HH5	-	187%	190%	200%
HH6	-	118%	122%	128%
Ethanol national average consumption (litres per capita)	**93**	**445**	**450**	**468**
Fuel wood national average consumption (kg per capita)	**143**	**80**	**80**	**84**
Charcoal national average consumption (kg per capita)	**4**	**2**	**2**	**2**

Source: Author`s elaboration

Figure 6.7 - Biomass per capita consumption per class (toe)



Source: Author`s elaboration

In LES and LES-Tr, apart from the shift to renewable fuels, lower private mobility demand reduces gasoline and diesel consumption significantly. As mentioned before, liquid fuels also include LPG used for cooking, for which consumption decreases due to residential energy savings.

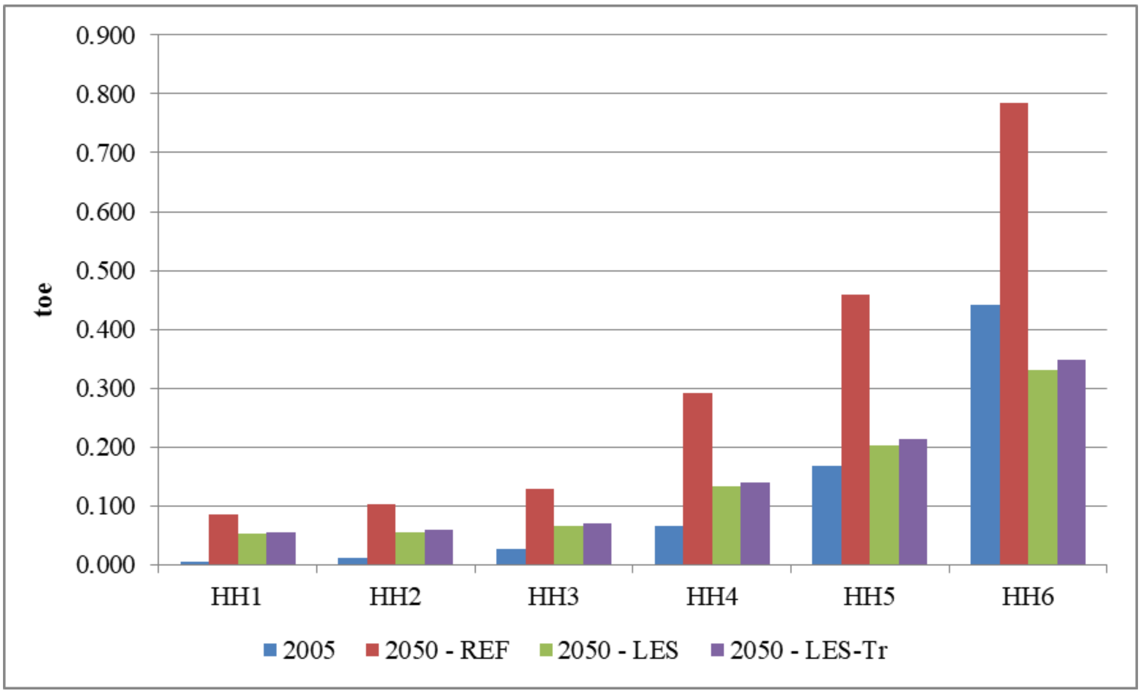
Table 6.15 - Liquid fuels per capita consumption per class (toe), variation (%) and national average (litres per capita or kilograms per capita)

	2005 Base year	2050 REF	2050 LES	2050 LES-Tr
HH1	0.01	0.08	0.05	0.06
HH2	0.01	0.10	0.06	0.06
HH3	0.03	0.13	0.07	0.07
HH4	0.07	0.29	0.13	0.14
HH5	0.17	0.46	0.20	0.21
HH6	0.44	0.78	0.33	0.35
HH1	-	1375%	799%	860%
HH2	-	775%	374%	404%
HH3	-	402%	158%	174%
HH4	-	346%	103%	115%
HH5	-	173%	20%	27%
HH6	-	78%	-25%	-21%
Gasoline national average consumption (litres per capita)	**67**	**303**	**124**	**131**
LPG national average consumption (kg per capita)[71]	**28**	**30**	**25**	**26**

Source: Author`s elaboration

[71] Considering the following density values for LPG:
2005: 550 kg /m^3 (EPE, 2006)
2050: 552 kg /m^3 (EPE, 2016)

Figure 6.8 - Liquid fuels per capita consumption per class (toe)



Source: Author`s elaboration

Public Transportation

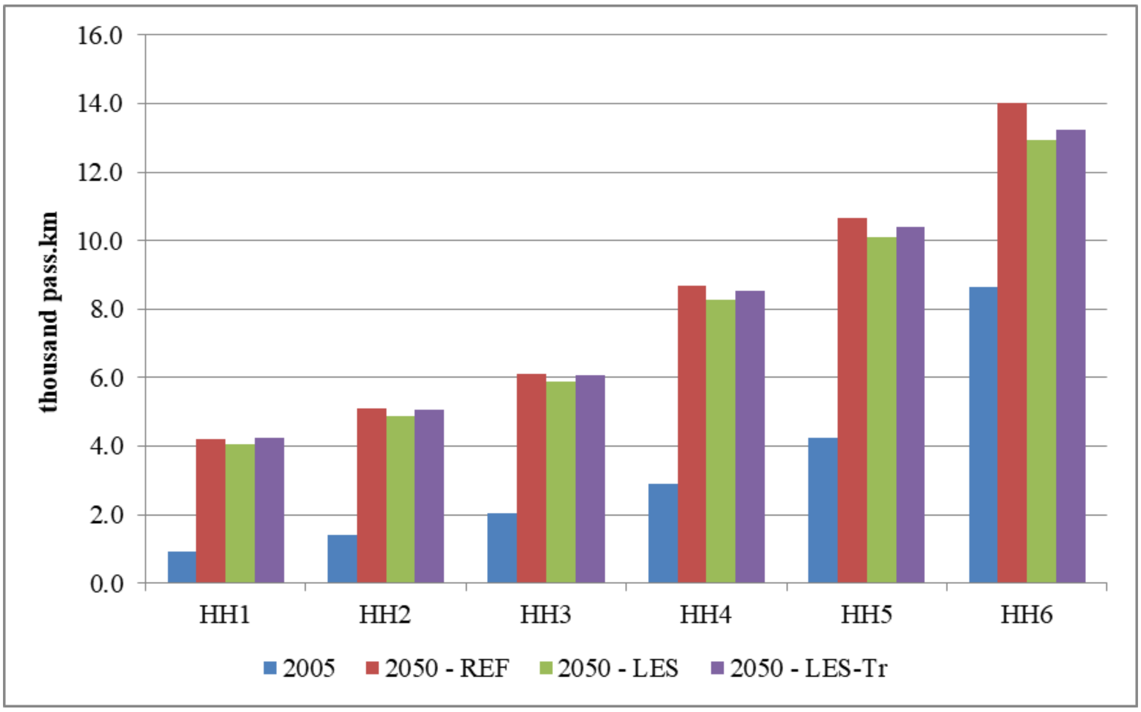
Transport activity grows significantly from 2005 to 2050, in accordance to economic performance and income gains. In lifestyles scenarios, non-motorized transportation and reduced mobility demand decrease total passenger activity in absolute terms, alongside with a shift to public transportation. In the aftermath, final demand for public transportation does not vary substantially across the three scenarios.

Table 6.16 - Public transportation per capita demand per class (thousand pass.km) and variation (%)

	2005		2050	
	Base year	REF	LES	LES-Tr
HH1	0.92	4.20	4.07	4.23
HH2	1.40	5.08	4.89	5.07
HH3	2.04	6.12	5.87	6.08
HH4	2.88	8.66	8.28	8.55
HH5	4.23	10.64	10.09	10.40
HH6	8.63	14.02	12.93	13.23
HH1	-	355%	341%	358%
HH2	-	263%	249%	262%
HH3	-	200%	188%	198%
HH4	-	201%	187%	197%
HH5	-	151%	138%	146%
HH6	-	62%	50%	53%

Source: Author`s elaboration

Figure 6.9 - Public transport per capita demand per class (thousand pass.km)



Source: Author`s elaboration

In the alternative scenarios, due to the increased mobility demand met by public transportation, the distribution of total passenger momentum is similar to base year levels (half is met by public, half is met by private transportation), despite major income gains[72].

---

[72] Considering the following ratios for private passenger transportation, according to D´AGOSTO *et al.* (2017 in LA ROVERE *et al.* (2017)):

2005: 0.0547 toe/thousand pass.km

2050: 0.0487 toe/thousand pass.km

Table 6.17 - Transportation momentum per capita (thousand pass.km) and share (%)

	2005	2050		
	Base year	**REF**	**LES**	**LES-Tr**
Total	**5.8**	**17.8**	**14.5**	**15.1**
Private	2.9	10.1	7.2	7.6
Public	2.9	7.7	7.3	7.5
Share of private (%)	**50%**	**57%**	**50%**	**50%**
Share of public (%)	**50%**	**43%**	**50%**	**50%**

Source: Author`s elaboration

Food

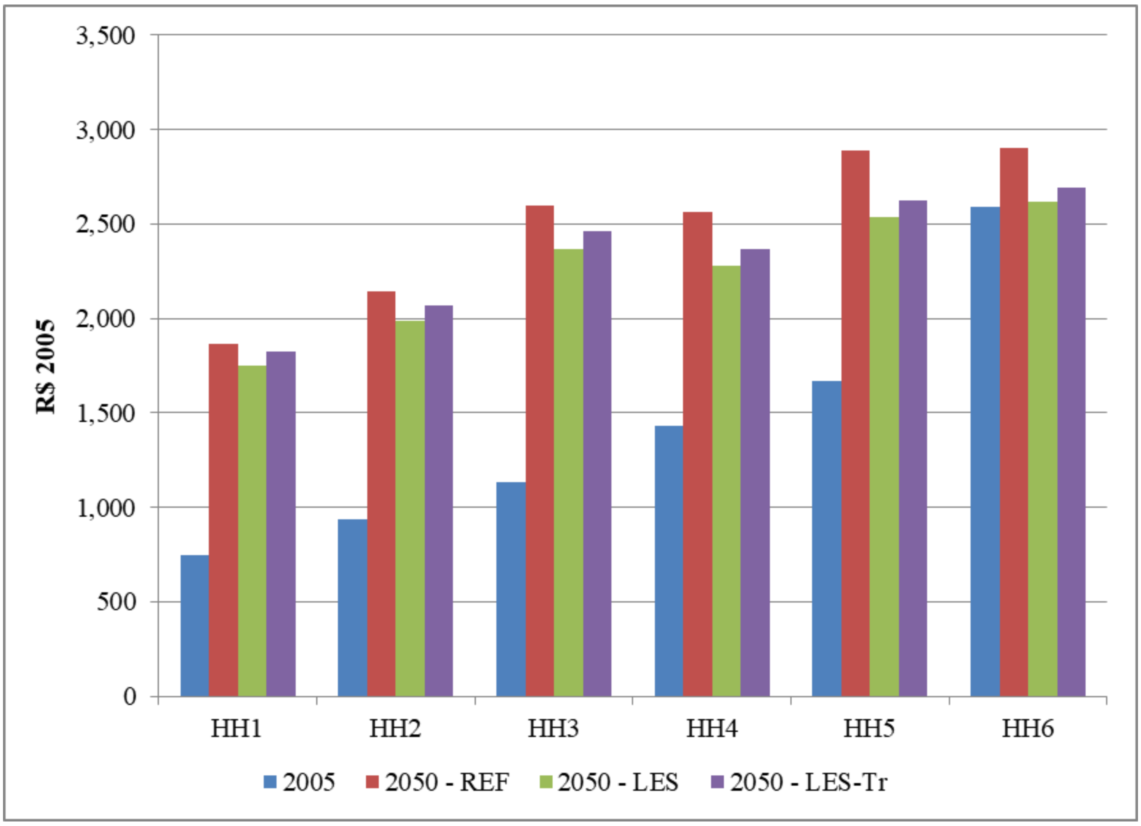
Food consumption within the household increases way below income gains in all scenarios, as demand reaches saturation. As explained in the previous chapter, base year consumption levels are already close to recommended standards (average daily intake of 2,044 kcal in 2008 according to (IBGE, 2011)). In addition, the richer the household, the more it spends with food out of the household, which is included in the services sector. In lifestyles scenarios, reduced waste leads to lower demand levels, even though the shift to such diets requires higher daily intake quantities (see PERNOLLET *et al.* (2017) and Table AII.5 in Annex II).

Table 6.18 - Food per capita expenditure per class (R$2005) and variation (%)

	2005		2050	
	Base year	**REF**	**LES**	**LES-Tr**
HH1	747	1,866	1,747	1,827
HH2	937	2,146	1,986	2,071
HH3	1,132	2,596	2,367	2,463
HH4	1,431	2,567	2,281	2,369
HH5	1,668	2,890	2,536	2,626
HH6	2,589	2,904	2,618	2,695
HH1	-	150%	134%	145%
HH2	-	129%	112%	121%
HH3	-	129%	109%	117%
HH4	-	79%	59%	66%
HH5	-	73%	52%	57%
HH6	-	12%	1%	4%
Per capita national average (R$ 2005)	**1,326**	**7,280**	**6,579**	**6,834**

Source: Author`s elaboration

Figure 6.10 - Food per capita expenditure per class (R$2005)



Source: Author`s elaboration

Other goods and services

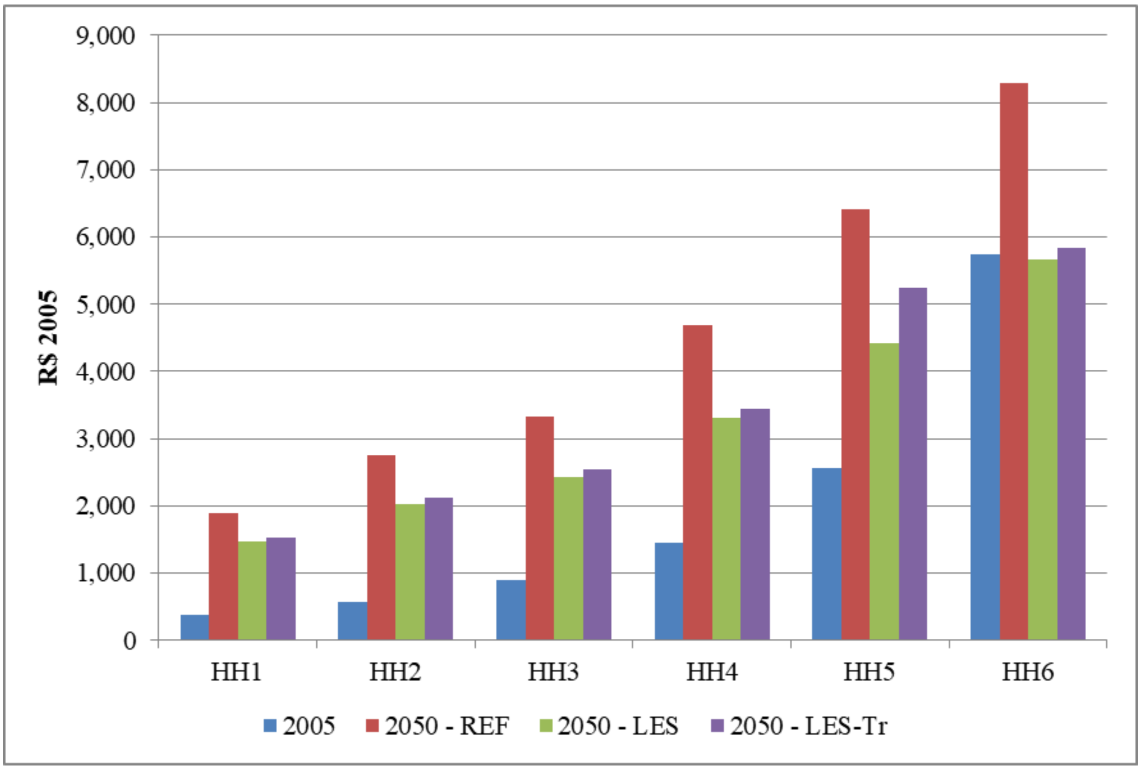
As households adopt a more sound behaviour regarding durable goods in general, expenditure levels decrease remarkably. With a smaller budget share devoted to energy, transportation and consumer goods, households allocate higher amounts in services, which include leisure, sports, entertainment, health, education, among others. Altogether, they shift to a dematerialized consumption pattern.

Table 6.19 - Other goods per capita expenditure per class (R$2005) and variation (%)

	2005		**2050**	
	Base year	**REF**	**LES**	**LES-Tr**
HH1	377	1,893	1,459	1,526
HH2	577	2,753	2,028	2,114
HH3	898	3,318	2,436	2,534
HH4	1,443	4,694	3,308	3,435
HH5	2,555	6,407	4,412	5,241
HH6	5,737	8,292	5,674	5,841
HH1	-	403%	288%	305%
HH2	-	377%	251%	266%
HH3	-	270%	171%	182%
HH4	-	225%	129%	138%
HH5	-	151%	73%	105%
HH6	**-**	**45%**	**-1%**	**2%**

Source: Author`s elaboration

Figure 6.11 - Other goods per capita consumption per class (R$2005)



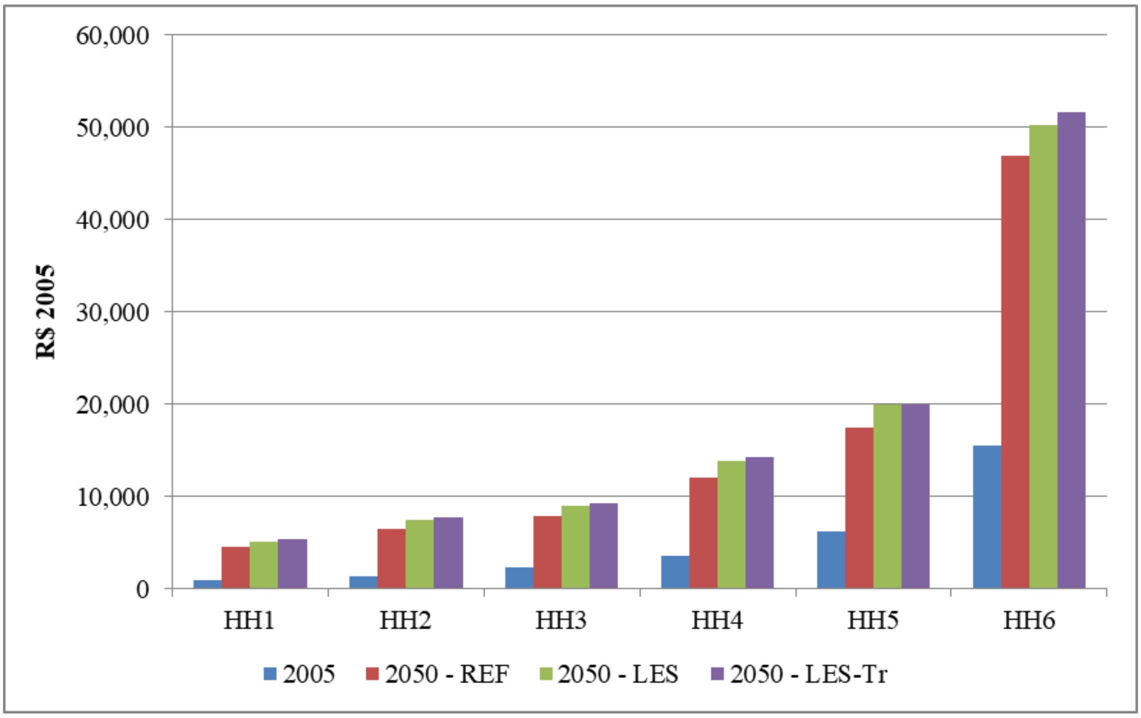
Source: Author`s elaboration

Table 6.20 - Services per capita expenditure per class (R$2005) and variation (%)

	2005		2050	
	Base year	REF	LES	LES-Tr
HH1	887	4,569	5,112	5,345
HH2	1,405	6,533	7,384	7,698
HH3	2,327	7,866	8,940	9,303
HH4	3,504	11,991	13,790	14,322
HH5	6,236	17,395	19,961	20,003
HH6	15,516	46,868	50,202	51,677
HH1	-	415%	476%	503%
HH2	-	365%	425%	448%
HH3	-	238%	284%	300%
HH4	-	242%	294%	309%
HH5	-	179%	220%	221%
HH6	-	202%	224%	233%

Source: Author`s elaboration

Figure 6.12 - Services per capita expenditure per class (R$2005)



Source: Author`s elaboration

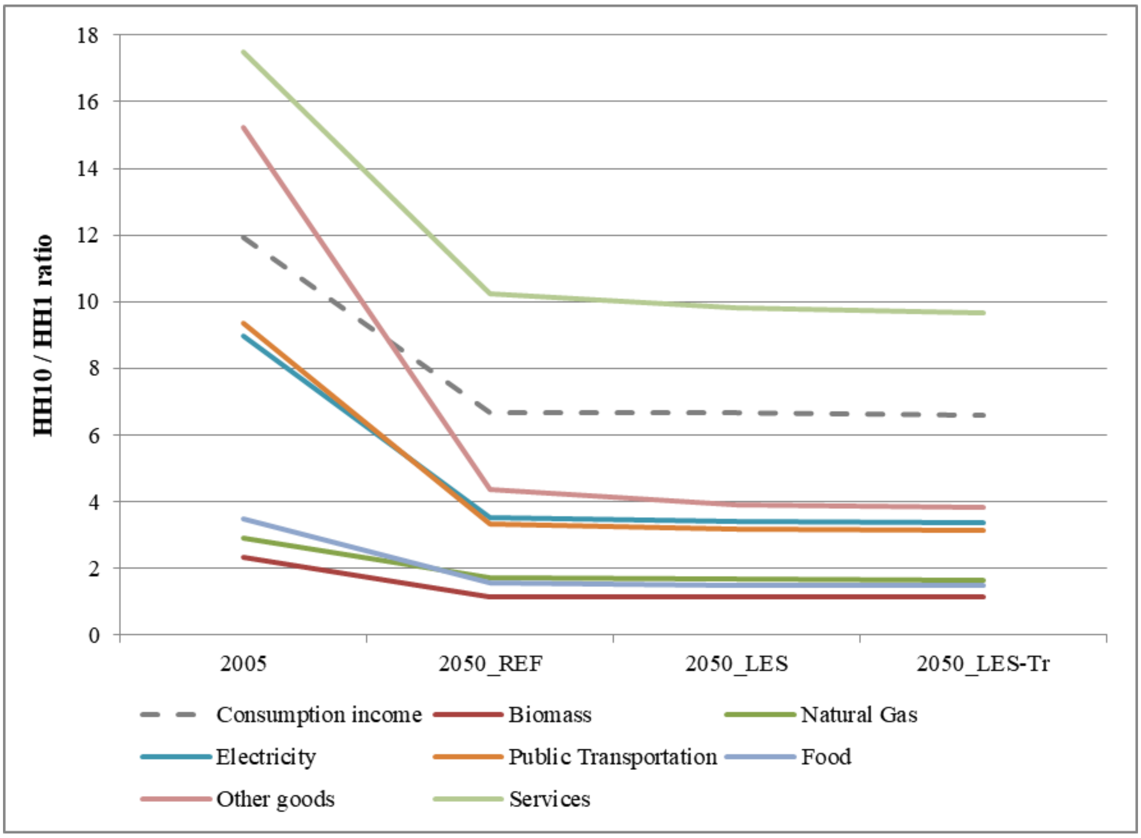
The table and figure below show the difference in income and expenditure levels for the various categories between the 10% richest households relative to the 10% poorest`. In 2005, per capita consumption budget for HH10 was nearly 12 times higher than HH1`s. For some consumption categories, however, the gap in expenditure levels was much higher, reflecting very different patterns of budget allocation. Consumption of oil products was more than 75 times higher, explained by the private car ownership, whereas differences in food consumed within the household was only 3.5 higher. Electricity requirements in the top decile were 9 times higher, due to differences in appliance ownership and use (see GROTTERA *et al.* (2018) for a detailed assessment of appliances in Brazilian households). In 2050, the gap between HH10 and HH1 is much narrow, the largest being in services, with the top decile consuming nearly ten times more than the bottom class.

Table 6.21 - Difference in per capita consumption income and expenditure levels between 10% richest and 10% poorest households (HH10 / HH1)

	2005		2050	
	Base year	REF	LES	LES-Tr
Consumption income	11.9	6.7	6.7	6.6
Biomass	2.3	1.1	1.2	1.1
Natural Gas	2.9	1.7	1.7	1.6
Oil products	76.9	9.3	6.4	6.3
Electricity	9.0	3.5	3.4	3.4
Transport	9.4	3.3	3.2	3.1
Food	3.5	1.6	1.5	1.5
Other goods	15.2	4.4	3.9	3.8
Services	17.5	10.3	9.8	9.7

Source: Author`s elaboration

Figure 6.13 - Difference in per capita consumption income and expenditure levels between 10% richest and 10% poorest households (HH10 / HH1) [73]



Source: Author`s elaboration

6.3 GHG emissions results

Total GHG emissions in 2050 are lower than base year in all scenarios, even the reference one. As explained in section 5.2, REF is not a ‘business-as-usual’ scenario, for public policies aiming at reducing emissions are put in place, ranging from curbing deforestation, improving agricultural and cattle ranching techniques, investing in public transportation and energy efficiency, among others. In the residential sector specifically, energy efficiency gains are achieved by replacing incandescent bulbs by fluorescent and LED ones, expanding the natural gas supply grid replacing LPG, and replacing old appliances by more efficient ones. In private transportation, there is a shift from gasoline and diesel to biofuels, combined with more efficient internal combustion

[73] Results for oil products are not depicted to favour figure scale and visualization.

engines and the penetration of electric vehicles. In the reference scenario, total emissions are 40% lower than in 2005. Behaviour shifts contribute to reducing total GHG emissions at some additional 11% in LES and 8% in LES-Tr. Compared to the reference case, total emissions are 18% and 14% lower in 2050 for these scenarios, respectively.

Between 2005 and 2050, there is a threefold increase in GDP. With GHG emissions decreasing in absolute terms, emissions per unit of GDP reduce significantly, up to 85% in the alternative scenarios. Comparing the lifestyle change scenarios to the reference case, emissions per GDP decrease is lower than total emissions decrease in LES, since GDP levels are lower than REF. In LES-Tr, with GDP levels similar to REF, the variation is the same for both indicators.

Table 6.22 - Total GHG emissions (MtCO2e) and emissions per unit of GDP (tCO2e/thousand 2005 USD)

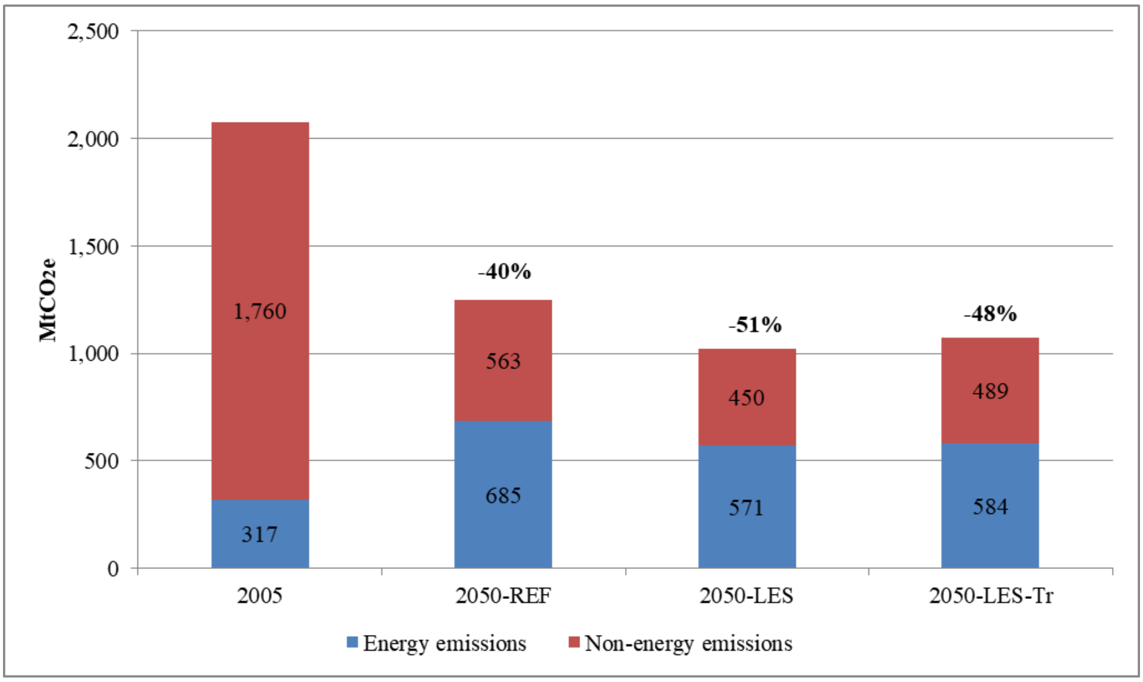
	2005		2050	
	Base year	**REF**	**LES**	**LES-Tr**
Total GHG Emissions ($MtCO_2e$)	2,077	1,248	1,020	1,073
Variation relative to 2005 (%)	-	-40%	-51%	-48%
Variation relative to REF (%)	-	-	-18%	-14%
Emissions per GDP (tCO_2e/thousand 2005 USD)	2.36	0.42	0.35	0.36
Variation relative to 2005 (%)	-	-82%	-85%	-85%
Variation relative to REF (%)	-	-	-16%	-14%

Source: Author`s elaboration

Absolute emissions reductions come from efforts to curb deforestation, which depart from very high levels in base year. In contrast, energy-related emissions actually increase, even in changing lifestyles scenarios. Urbanization, higher per capita income and economic growth induce higher energy demand. In addition, before 2050 all the hydropower potential that is considered economically feasible and environmentally sound is deployed and fossil energy is expected to increase its share in power generation, even though other renewable sources such as wind and solar also expand.

In LES, the reduction in energy and non-energy related emissions is similar in absolute terms (114 $MtCO_2e$). In LES-Tr, non-energy related emissions decrease less than energy, mainly explained by higher output in the agriculture and agroindustry sectors, including exports of meat products.

Figure 6.14 - Energy-related emissions and non-energy related emissions per scenario (MtCO2e)



Source: Author`s elaboration

Despite significant GDP and GDP per capita growth, emissions per capita decrease significantly from 2005 to 2050, in all scenarios. As population is 22% larger than in base year, per capita emissions decrease even more than total emissions, between 51% and 60%. Nonetheless, the opposite occurs to energy-related ones, as discussed above. In the reference scenario, energy-related emissions per capita increase 77% but in the lifestyles scenarios, they grow significantly less (Table 6.23).

Table 6.23 - Per capita GHG emissions results (tCO2e/capita)

	2005	2050		
	Base year	**REF**	**LES**	**LES-Tr**
Emissions per capita (tCO_2e/capita)	**11.23**	**5.5**	**4.5**	**4.7**
Variation relative to 2005 (%)	-	-51%	-60%	-58%
Variation relative to REF (%)	-	-	-18%	-14%
Energy-related emissions per capita (tCO_2e/capita)	**1.71**	**3.0**	**2.5**	**2.6**
Variation relative to 2005 (%)	-	77%	47%	51%
Variation relative to REF (%)	-	-	-17%	-15%

Source: Author`s elaboration

Lower income classes' energy emissions are very low in 2005, for these households have little access to consumer goods and private transportation, and many rely on traditional biomass to meet their basic needs regarding food and shelter. As they improve their income levels and start spending on fuels for private vehicles, electronic devices, among others, their energy demand increases substantially. Energy emissions grow way above consumption income in the reference scenario, except for the top income class (HH6) (see Table 6.24). The higher grid emissions factor may also contribute to the associated GHG emissions increase. In the lifestyle change scenarios, the richest households actually decrease or keep their energy emissions compared to base year. This is possible not only due to reduced demand for energy demanding goods, but also because they shift from fossil fuels to biofuels for private transportation. For the bottom classes energy-related emissions still increase more than consumption income.

Table 6.24 – Households` energy emissions variation from 2005 to 2050 (%)

	2050		
	REF	**LES**	**LES-Tr**
HH1	1639%	1013%	1093%
HH2	953%	502%	543%
HH3	518%	235%	257%
HH4	460%	169%	186%
HH5	240%	55%	64%
HH6	121%	-5%	0%
National average	**270%**	**78%**	**89%**

Source: Author`s elaboration

6.4 Comparison of model outcomes with analyses for other countries

As part of the ECOPA Project (see Introduction), the most relevant comparison of this thesis results is definitely with the project`s findings for the French economy, in spite of very different national contexts.

Analogously to the Brazilian exercise, simulations for France included a scenario in which a set of assumption exclusively related to behaviour changes is tested. They are contrasted to a baseline in which the National Low-Carbon Strategy (SNBC[74]) launched by the French government is put in place, attaining 140 $MtCO_2$ in 2050 (a fourfold decrease compared to 1990 levels).

The French scenario only accounts for energy-related emissions. Given that French population is expected to reach 72 million inhabitants in 2050, energy emissions should not exceed 60 $MtCO_2e$ to keep per capita levels consistent with the 0.8 tCO_2e/capita in 2050[75]. These calculations are similar to the ones performed for Brazil,

[74] Acronym for Stratégie Nationale Bas-Carbone.

[75] Energy-related emissions in 1990 were 360 $MtCO_2$.

based on the 2016 UNEP Emissions Gap Report (UNEP, 2016), detailed in section 5.1.3.

Assumptions regarding behavioural shifts are analogous to the ones chosen for Brazil, even though penetration levels may vary according to the county context. In brief, the main driver is a large dematerialization of household consumption. Expenditure dedicated to well-being, health, care, education, culture and sports increase strongly. The ICET technologies contribute to the dissemination shared services and lower equipment ownership rates. The ‘R Society’ is implemented: Reuse, Reduce, Repair, Recycle. The life cycle of goods and components is much longer. Second-hand markets are large and dynamic. Food diet evolves with an increase of ‘flexitarian’ or vegetarian people. The complete quantification of assumptions can be found in BARBIER *et al.* (2018). New consumption levels provide the expected variation in budget shares for all categories of expenses.

As in results for Brazil, notwithstanding major shifts towards a less carbon-intensive consumption pattern, French emissions in 2050 are still far above desired levels: 5.1 tCO_2e per capita (energy emissions only). They are actually much higher than energy-related emissions attained in corresponding scenarios for Brazil, including the reference scenario (3.0 tCO_2e per capita in REF and 2.5 tCO_2e per capita in LES). This is consistent with higher per capita levels of income and expenditure in France compared to Brazil.

The French exercise explores another alternative pathway in which the consumption shifts are complemented with additional assumptions on (i) energy efficiency in end-use sectors (industry, agriculture, transport, buildings) and other structural changes; (ii) decarbonization of energy production, electrification of end-uses and penetration of bioenergy and (iii) other supplementary assumptions (e.g. twice less freight needs of the economy in 2050 compared to 2010).

Even so, the final level of energy-related emissions is still twice the defined target: 117 $MtCO_2$, corresponding to 1.6 tCO_2 per capita. In order to meet the 1.5^oC target (0.8 tCO_2e per capita), even deeper policies and measures ought to be pursued.

In DAI *et al.* (2012), a hybrid recursive CGE model simulates Chinese households shifting towards a dematerialized consumption pattern up to 2050. This entails major structural changes in the Chinese economy, namely in the textiles and other industrial sectors. This is explained by the large share of household budget devoted to durable goods in 2050, higher than the reference scenario for this study. In contrast, they devote a smaller share to services in the baseline, so the expansion of this sector is more expressive in China than in the Brazilian scenario (28.6% growth in the miscellaneous services sector in China, against 5.7% increase between REF and LES in Brazil). As for Brazilian households, the consumption of industrial products, transport and services increases much more than food and agricultural products. While in Brazil behavioural shifts lead to a 6% reduction in Electricity activity, in China the impact is a 16.9% decrease. Regarding fossil energy, the impact on oil derivates is more intense in the Brazilian economy (-19.7%, against -6.6% in China), whereas the impact on coal the opposite occurs (-11.7% in Brazil against -16% in China).

While in the Brazilian scenario impacts on trade balance are minor, in China they are more intense (22% lower exports levels of industrial sectors and 14% decrease in overall exports). They may be due to the Chinese model`s recursive nature, and a more sophisticated treatment of investment dynamics – the authors explain that investment leaves energy intensive industrial sectors and is allocated in services to meet household demand. Decreased exports from industrial sectors contribute largely to lowering GHG emissions in China.

This thesis` findings can hardly be compared to those on SHUKLA *et al.* (2008) for their scenario assumes a whole mindset transition towards a sustainable society, comprising supply side actions (that include unconventional options such as CCS) and demographic aspects. Moreover, a carbon tax is implemented, entailing endogenous technical changes. However, the role of a few behavioural shifts may be highlighted.

For a total amount of 62.6 billion tons of CO_2 emissions avoided between 2005 and 2050 in India, reduced consumption accounts for 13%, and modal shifts in transportation 14%. Recycling explains 2% of total mitigation. Table 2.2 in Chapter 2 can be revisited for all mitigation options.

6.5 Comparison of model outcomes with other analyses for Brazil in similar contexts

Results show that lifestyles changes alone cannot deliver the reduced emissions-intensity that is required to stabilize emissions at safe levels. Households represent a major share of final demand in the Brazilian economy (62.5% of GDP in 2014), but Brazil`s emissions are closely related to cattle-raising and agricultural practices, which are partially driven by international demand (see MCALPINE *et al.* (2009) for evidence). A significant share of oil and industrial products is also destined to exports.

In addition, most consumption patterns changes require political will. An emblematic example concerns public transportation: without infrastructure investments and public policy efforts, individuals cannot shift from private vehicles to subways, buses or bicycle lanes.

In this context, contrasting results to other initiatives that focus on mitigation actions from the supply-side is underlying.

6.5.1 IES-Brasil 2050 - Implicações Econômicas e Sociais de Cenários de Emissão de Gases de Efeito Estufa no Brasil até 2050

In this study, LA ROVERE *et al.* (2018) use a more sophisticated version of the Imaclim-BR model, that include a few recursive features (see section 4.2.4 for details) to simulate an emissions pathway consistent with stabilizing temperatures levels at 1.5^{o}C above pre-industrial levels. Emissions per capita should not exceed 0.8 tCO_2e in 2050, as explained in section 5.1.3.

Mitigations actions are implemented across virtually all sectors alongside a tax on burning fossil fuels from 2021 on, starting at modest levels and reaching 100 US$/$tCO_2e$. Carbon revenues are used to replace payroll taxes, softening recessive effects that may accrue from taxation. Emissions drop 83% compared to the baseline scenario, which is similar to the one considered in this thesis (dropping from 1,088 $MtCO_2e$ to 187 $MtCO_2e$).

The decarbonization scenario benefits from the huge mitigation potential from agriculture, husbandry and forestry, with many cost-effective actions. According to STRASSBURG *et al.* (2014), efficiency gains and agricultural techniques that provide win-win solutions determine that is it possible to increase crop and herd outputs with no extra land clearing than that currently available. Moreover, there is a large mitigation potential in cattle raising to be tackled (BUSTAMANTE *et al.*, 2012). A significant increase in cattle ranching productivity (annual meat production per unit of pasture area) is achievable through investments in pasturelands - better fodder grass selection and use of forage legumes, tillage reduction, electric fencing among other options - and in herd performance - breed selection, reproductive management and earlier slaughtering. Ranching intensification would deliver a double dividend by reducing the number of animals per unit of meat produced and therefore emissions per unit and by freeing land to other purposes, for example, reforestation and forestry. Moreover, the successful implementation of afforestation and reforestation activities lead to a dramatic increase of forest plantations using eucalyptus and pine trees, not only for pulp and paper and timber industries (including pellet production for exports) but also for renewable charcoal production used in the manufacturing of pig iron and steel. In fact, huge areas of degraded land are available in the country where these afforestation programs would be developed, achieving both environmental and economic benefits. It would also explore the forestry sector's sequestration potential, associated to the recovery of degraded pasture lands, native forest restoration and the expansion of commercial forests to provide biomass feedstock for power generation and other industrial purposes, which act as huge carbon sinks during the first years. Negative net emissions from the land use sector should more than offset the remaining emissions from agriculture and livestock.

In passenger transportation, emissions would drop due to the increased penetration of light transport vehicles (LTV), subways and buses (electric and hybrid) in cities in 2050. Electric cars reach a significant share of light-duty fleet in 2050, and the remaining ones are more efficient and run almost exclusively on ethanol.

Freight transportation emissions would drop due to efficiency and logistical gains and an increase of the shares of railways (including electrification of railways) and waterways. Emissions from trucks are reduced by the introduction of electric and hybrid trucks.

In the energy sector, improvements in refineries and oil and gas extraction processes contribute to reducing emissions, including fugitives. As coal mining activities virtually cease, associated fugitive emissions would drop to near zero in 2050.

In power generation, new installed additional capacity prioritizes renewables sources. Onshore wind, photovoltaic and thermal solar power increase substantially, although constrained by their intermittent character. Thermopower plants running on natural gas, coal and oil products operate until the end of their lifespan and, by 2050, are fully decommissioned.

Renewable biomass offers promising perspectives for power and heat generation, thanks to Brazil's large land, water and natural resources endowment. The expansion of ethanol for passenger transportation provides large amounts of sugar cane bagasse and straw that can be used for power generation. Charcoal, pellets, brickets and residual forest products are made available for power and heat generation, in line with national reforestation goals and the expansion of commercial forests. Biomass-fired thermopower generation contributes to meeting electricity demand in dry periods of the year when hydropower generation decreases. The power sector fully decarbonizes by 2050, with some remaining non-CO_2 emissions coming from biomass use.

Industrial emissions decrease due to energy efficiency gains and higher electrification rates in all sectors. Charcoal partially replaces coke from coal in pig iron and steel manufacturing, and in the cement sector, fossil fuels are also partially replaced by biomass and the use of clinker is reduced by the addition of pozzolans. Methane capture in urban solid waste landfills, sewage systems and industrial plants increases and a share is used to generate electricity.

Compared to the reference case, the 1.5^{o}C scenario leads to minor GDP losses (-1.0%) and increased investment rates, due to the additional investment requirements for mitigation. The price index variation is, however, significantly higher in the decarbonization pathway (up to 42% relative to 2015, against a 15% rise in the reference scenario), affecting households` purchasing power, although this does not jeopardize food and energy security, which is similar to this thesis findings. In short, this shows that the pursuit of a pathway consistent with safe GHG stabilization levels is feasible without severely hindering economic performance.

6.5.2 Opções de Mitigação de Emissões de Gases de Efeito Estufa em Setores-Chave do Brasil

This project (MCTIC, 2018) contrasts a reference scenario with different low-carbon pathways in which 'best-available-technologies' are applied to yield emissions reduction in key sectors. Macroeconomic impacts are assessed for three levels of carbon taxation: 0 US$/t$CO_2$e, 25 US$/tCO_2e and 100 US$/t$CO_2$e.

The underlying difference compared to 'IES-Brasil 2050' (LA ROVERE *et al.*, 2018) is that this study uses a cost-optimization approach, and the fulfilment of the NDC is not taken into account as a current policy in the reference scenario. As a result, the share of fossil energy is much higher, and conversely to 'IES Brasil – 2050', in the reference scenario emissions increase compared to 2005 levels, reaching 2,070 MtCO_2e in 2050. In low-carbon scenarios, emissions are 18%, 31% or 42% lower than the reference case in 2050, for 0, 25 and 100 US$/t$CO_2$e tax levels, respectively.

Impacts on GDP are negligible for tax levels at 0 and, 25 US$/t$CO_2$e. At a 100 US$/tCO_2e carbon tax, GDP reduces 0.83% in relation to reference scenario if no recycling scheme is put place. In contrast, GDP actually increases in the case carbon revenues are paid to government (+0.2%) or to households (+0.09%).

6.5.3 Mudança do clima - Avaliação dos reflexos das metas de redução de emissão sobre a economia e a indústria brasileira

Undertaken by FIESP, this study simulates different policy scenarios for the Brazilian economy between 2015 and 2050, with a special focus on industrial sectors, using the EPPA model. This is a global recursive CGE with a cost-effectiveness approach in which Brazil is one among 16 world regions. Flows among countries are represented using data from GTAP.

Scenarios test different levels of ambition, both for Brazil and for other countries, according to NDC pledges. In the reference scenario no mitigation efforts are considered; in an intermediary scenario the NDC is implemented up to 2030 and ambition levels are kept up to 2050, similar to this thesis` reference case. A third scenario considers that mitigation efforts are intensified after 2030, beyond NDC ambition levels. Different economic instruments are also taken into account, such as taxation and emissions trading schemes, apart from assuming implicit incentives capable of enhancing renewable energy deployment and improvements in land use policies and techniques.

Similar to results in MCTIC BRASIL (2018), in the business-as-usual case, GHG emissions are higher in 2050 than in 2005. In a scenario in which no further efforts beyond the NDC are considered, emissions resume after 2030, even though they are kept below 2005 levels. However, as in the results` in this thesis, energy-related emissions grow (as well as waste and IPPU emissions). In this case, and with no explicit carbon pricing schemes, GDP losses are indeed minor, less than 3% in 2050 compared to the baseline. Deepening the ambition of NDC pledges up to 2050 is proven fairly ineffective. Policies based on curbing deforestation, recovering degraded pasturelands and fostering renewable energy are no longer able to deliver the required emissions reductions without severe economic costs (18% reduction in GDP in 2050 compared to reference scenario).

Explicit carbon pricing mechanisms are indicated to reduce GHG emissions in 60% relative to 2005 levels. In such cases, the study shows that emissions trading schemes are nearly twice more effective than sectoral taxation, yielding a 3% GDP reduction in 2050 compared to the reference case, against a 6% loss for a carbon tax.

This study stands out for providing a comparison with other countries, therefore deeper insights on competitiveness. It shows that under a cap-and-trade system, economic costs in Brazil in 2050 would be similar to those faced by the US, the European Union and the rest of Latin America, but significantly higher than China and India, which can be explained by the low degree of ambition of these countries` NDCs.

6.6 Further research

While acknowledging the limitations of this study, we profit to point out a few possible developments as suggestions for future research, regarding the framing of transition scenarios and possible implications for modelling.

6.6.1 Framing a sustainable society

A complete long-run scenario coupling behavioural shifts and supply-side actions should definitely be considered. It would allow for identifying to what extent consumer strategies are enabled and benefit from technological developments and policy efforts. For instance, investments on public transportation infrastructure can increase and incentive households` possibilities to relinquish the use of private vehicles, as in the 'High-Shift Scenario' in ITDP (2014)[76]. On the other hand, it should be stressed that actions that pursue energy efficiency or fuel replacement, directly reducing the carbon intensity of goods and services (e.g. carbon neutral power sector) could diminish the mitigation potential of some demand-side efforts.

This could be the first step into modelling an effective 'sustainable society scenario' - encompassing efforts from all actors (households, government, the private sector) – in which mitigation is mainstreamed into the development pattern and able to realise non-climate objectives (see SHUKLA *et al.* (2008)).

[76] The analysis by ITDP (2012), provided at the world level but at a great extent valid for Brazil, states:

"The analysis underlying the High Shift scenario suggests that urban travel needs in most parts of the world can, in principle, be met with a combination of travel modes that cut urban light-duty vehicle (LDV) kilometers by half. The required extent and use of mass transit and non-motorized modes in all areas in 2050 does not exceed the use in certain areas of the world today. However, given the rapid urbanization occurring between now and 2050, this will require public transportation to be typically two to three times higher in 2050 in High Shift than in the baseline, and in some regions many times higher than today in places where today's public transport levels of service are very low." (p. 13)

Most existing low-carbon scenarios fail to do so, for they focus mostly on the technical fix and mitigation actions take place at the margin of the economic development frontier. Conversely, scenarios that solely account for behavioural change either represent a desirable society, regardless of the level of action.

As explained by SCHANES *et al.* (2016), consumers` practices are largely shaped by infrastructures, social norms and habits that limit their ability to act . Upstream impacts of available goods and services may be unknown or undetectable (GRUNWALD, 2010 in SCHANES *et al.* (2016)). Therefore, if the carbon intensity of products remains unchanged, changes in consumption can only yield marginal – and insufficient – outcomes.

Ideally, such framework should also encompass explicit carbon pricing mechanisms. A well-designed tax on carbon emissions would entail further technical change towards more efficient and less carbon-intensive production. At the same time it could act as an economic incentive for less consumerism (BROWN; VERGRAGT, 2016).

It should be stressed that an ideal sustainable society scenario must aim beyond the sheer coupling of behavioural shifts and supply-side actions. Ground assumptions regarding demographic rates, urbanization trends, globalization and international trade, among others, ought to be re-evaluated. Concerning household behaviour specifically, time-allocating decisions may need to be reconsidered. As households leave consumerism behind, they may opt for dedicating more time for leisure detrimental to work and this could affect labour supply in general.

6.6.2 Modelling developments

The fact that many characteristics of households change over time is underlying in this kind of research and must be further explored. In particular, specific assumptions that are taken universally must be fine-tuned at the class level. The demographic evolution rate and the evolution of active population are currently the same for all classes. However, it must be taken into account that, in general: (1) the number of household members in lower income classes is higher than in top ones; (2) the average

age of head of the household is higher in top classes; (3) the share in rural households is higher in lower income classes.

Therefore, it is likely that bottom households will grow at faster rates than top ones, once they migrate and become urban, and also due to higher fecundity rates (given the household size and average age). Current assumptions possibly underestimate bottom deciles in terms of number of households, while overestimating top ones in final year. Educational levels should improve more in bottom deciles as well. This assumption is implicitly considered in the changing labour income distribution structure. However, it should also have significant implications on public budget, regarding social security contributions and benefit payments. Public transfers to households are currently indexed to GDP per capita evolution, therefore varying alike for all classes. This should be further explored.

Another key point concerning educational levels is the disaggregation of labour. section 4.2.3.3 presents the outputs on workforce data calibration – the labour factor is split into six categories according to degree of skill and formality. Notwithstanding the efforts to outline workers` profile, no simulation using Imaclim-S BR managed to apply different levels of skills. Barriers include the lack of inputs to subsidise assumptions (how the level of skill evolves across different classes, how demand for different skill labour types evolves across sectors, how this affects labour productivity, etc.). Moreover, further investigation on the theoretical framework on how to model the substitutability and complementarity of production factors (within skill levels but also regarding capital and energy) is needed (see section 3.8 for a discussion on this topic). To what extent this should affect total factor productivity remains unclear.

Such endeavours should help disentangling the interplay between jobs, wages, formality levels, income and consumption, providing a deeper notion of potential implications of policy scenarios. Complementarily, it would help elucidating price formation dynamics, given that labour costs are a strong determinant of price levels.

Concerning modelling issues specifically, it should enable to reduce the inflexibility of Gini coefficient outcomes currently noticed. Provided that sectors have different labour skill requirements and remuneration levels, it would be especially relevant on scenarios with explicit carbon pricing mechanisms, in which major structural changes can take place (GROTTERA *et al.*, 2016b). In addition, different carbon revenues recycling schemes have significantly varying impacts on income distribution and welfare (BRENNER *et al.*, 2007; CHEN *et al.*, 2013; GONZALEZ, 2012; GROTTERA *et al.*, 2015; HEERDEN *et al.*, 2006; LEFÈVRE, 2016). However, the household demand function used in this simulation (exogenously defined consumption budget share per category – see equation 61 in Annex I), is unable to capture demand responses to price changes arising from taxation. The introduction of a carbon tax would require the formulation of a demand function that simultaneously embarks the convergence of consumption patterns and price elasticities.

7 Conclusion

In a world that is about to experience unprecedented levels of demography, income, urbanization and trade activity, understanding how consumption patterns will evolve is underlying for drawing implications in energy trends and greenhouse gases emissions. The bulk of population and income growth shall take place in developing countries, where current levels of per capita energy use and emissions are remarkably lower than the world average. This is the reflection of insufficient levels of basic services provision, such as water supply, adequate transport infrastructure, access to modern sources of energy and food.

Notwithstanding the unquestionable need to improve living standards in the developing world, a major concern is that, in the case these countries mirror current western consumption patterns, the window for climate action should close inexorably soon. In this sense, the mitigation potential of changing consumption patterns – or lifestyles in a broader understanding – has been increasingly acknowledged. On the one hand, many possibilities of reducing the GHG intensity of products are yet to be proven technical and economically feasible, as it is the case of electric vehicles and energy storage technologies. On the other hand, no realistic options are foreseen for animal food and air travel, for instance. Therefore, structural changes in consumption patterns might be needed.

While endorsing behavioural shifts as an important lever for climate action, a growing body of literature explores what new consumption patterns might look like and their potential contribution for reducing emissions. Since they usually apply accounting techniques or life-cycle assessments, they nevertheless fail to estimate the overall impacts of structural shifts, namely on economic growth, jobs, prices and socioeconomic implications in general.

This thesis sought to contribute to the debate on this topic by embarking the quantification of consumption shifts into a macroeconomic framework, namely a hybrid computable general equilibrium model, the Imaclim-S BR. By doing this, we wish to enhance the modelling relevance for supporting policy decision. Modelling efforts undertaken during this thesis did not concern the development of the Imaclim-S BR tool *per se*, but rather the representation of households and labour supply into the dataset. In fact, the underlying mechanisms through which Imaclim-S BR functions have been extensively discussed in previous works. We hope the reader does not feel such aspects have been too overlooked in this study, contributing to the general perception of 'black box' often associated to CGE models.

The choice to disaggregate households in Imaclim-S BR arises from identifying that most CGE models applied in climate research in Brazil were unable to address development issues related to mitigation policies. Understanding the implications on poverty, income inequality and consumption levels of the poorest stratum, to name a few, is underlying for subsidizing the climate agenda through a 'development first' approach.

A long-term mitigation scenario exercise for Brazil must take into account the persisting social disparities, regarding both income and regional aspects. For the Imaclim-S BR model, the choice for disaggregating households was based on the income criteria. Despite often applied in literature, this is not an evident choice for every developing country. Similar exercises for China could opt for distinguishing rural and urban households, as often done, whereas in South Africa splitting household by ethnical groups could be interesting.

The use of microdata from national household surveys allowed the outlining of the household sector in representative household groups (RHGs). The income and consumption profile was drawn from POF, whereas PNAD provided information on educational levels and degree of formality, enabling to better represent the workforce. The identified relations were brought into the Social Accounting Framework that is the base for Imaclim-S BR calibration – therefore assuring macroeconomic consistency – but not without having to overcome a few discrepancies between datasets, relative to differences in terminology and methodological approaches.

Splitting household into income groups proved an assertive choice. In the base year, the gap in per capita consumption expenditure between the 10% richest and the 10% poorest households was approximately 12 times. Moreover, this is reflected in very different consumption patterns and consumption budget allocation. While the top decile spends only 3.5 times more on food than the bottom one, its consumption of oil products (LPG and gasoline or diesel for private transportation) is more than 75 times higher. Such astonishing discrepancies cannot be ignored in prospective exercises focusing on GHG emissions.

A key assumption in long-term scenarios for Brazil is that income and living standards of the poorest will keep evolving faster than the richest, reflecting better education levels and the continuity of the social agenda put in place in the last decades. While attaining unprecedented levels of income, lower classes will gain access to consumer goods previously available exclusively to top ones – therefore partially or fully mimetizing their consumption pattern. Projections must be able to represent these trends in demography, income distribution and resulting consumption profiles.

Using historical consumption data to determine lower classes households` preferences would not capture such trends. Elasticities on income cannot capture leaps on consumption categories, for example when income gains allow households to purchase private vehicles or electric appliances. Either do they capture saturation trends for certain categories such as food, for which no additional consumption is expected once needs are satisfied. An alternative approach is to use Engel curves, which define the allocation of consumption budget into various categories according to the level of income. Engel curves for upper classes in 2005 (base year) were used as benchmark for determining consumption levels of lower income households in 2050, complemented with a few additional assumptions. Final consumption profiles for different household classes were then defined for the reference case, which is a revision of the PNE 2050 scenario found in the IES 2050 Governmental Planning Scenario. In effect, income and consumption gaps between the 10% richest and 10% poorest in 2050 are much narrower than in 2005. Hopefully, this makes a case on the shortcomings of using elasticities calibrated in past data to frame household behaviour by providing a more realistic consumption profile in the reference case.

A set of two alternative pathways was then considered, aiming at contributing to the debate on the relevance of consumption as a climate policy tool for mitigation. While pursuing a more energy-sober, dematerialized and less emissions-intensive consumption profile in general, households can contribute to mitigating 18% of GHG emissions compared to the reference scenario in 2050. A share of the reduction is nevertheless due to a recessive effect, as GDP is 2.6% lower. Interestingly, employment levels virtually do not change. This is the reflection of a shift in household demand towards services, detrimental to other less labour-intensive sectors. Apart from economic losses, the reduction in emissions also comes at the expense of a rise in price levels (8% higher than reference case).

Some of the negatively affected sectors are internationally competitive, namely the commodity-based ones. A second alternative scenario was then envisaged, presuming they manage to partially offset the reduction in internal demand by increasing exports (although hindered by higher domestic prices). In this case, GDP losses are avoided, and structural shifts in the economy are not as intense as in the previous case. With higher economic activity, especially in these emitting sectors, the reduction in emissions is lower, 14% relative to reference case. Some of these sectors pay above the average wages. Also does the services sector, for which the output variation is almost as high as in the first alternative scenario. Therefore, in the scenario with boosted trade activity, the impact on price levels is even heavier, and the implications for households` purchasing power are not negligible.

Options for reducing greenhouse gases emissions through technological progress and supply-sides actions in general are plenty. Recent long-term projections focusing on the implementation of the Brazilian NDC or even on more ambitious scenarios, consistent with a 1.5^{o}C target, have shown that many of them are cost-effective, while others require political will or have financial and technical barriers to overcome. Alternatives range from low-carbon agricultural techniques, intensification of cattle ranching, waste management, deployment of renewable sources in power generation and biofuels in transportation, improving energy efficiency in all sectors, waste management, among others.

The mitigation potential of supply-side actions is greater than of behavioural shifts. In order to provide the same level of mitigation, the extent of consumption shifts would have to be such that this would most likely jeopardize living standards, with possible implications for economic growth. However, this does diminish the importance of consumption for reducing emissions. Indeed, both approaches must be targeted, given that supply-side actions can enhance the mitigation potential of lifestyle changes by expanding consumers` possibilities and lowering the GHG intensity of products. The combination of demand and supply mitigation in simulations using Imaclim- S BR would require further exploration of demographic assumptions and labour dynamics. Modelling developments should also seek to develop a demand function able to simultaneously capture the evolution of consumption patterns according to income levels and consumers` responses to price variations that may stem from explicit carbon pricing policies.

A real sustainable society cannot be achieved without efforts of all natures, truly allowing for the realization of other development objectives rather than climate mitigation. In this sense, hopefully this thesis acts as a starting point for addressing critical questions concerning the role of consumers and lifestyle changes in supporting climate change mitigation.

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Annex I - Imaclim-S BR formulation

This section describes the whole technical structure of Imaclim-S BR. It is a summary and virtually the complete reproduction of LEFÈVRE AND WILLS (2013). The only exception is regarding household consumption, for which alternative formulations are described.

In short, the model`s comparative static framework boils down to a set of simultaneous equations, that are valid either for reference or policy projections:

$$\begin{cases} f_1\ (x_1,\ldots,\ x_n,\ z_1,\ldots,\ z_m) = 0 \\ f_2\ (x_1,\ldots,\ x_n,\ z_1,\ldots,\ z_m) = 0 \\ \ldots \end{cases}$$

$$f_n\ (x_1,\ldots,\ x_n,\ z_1,\ldots,\ z_m) = 0$$

with:

x_i, $i \in [1, v]$, a set of variables (as many as equations),

z_i, $i \in [1, p]$, a set of parameters,

f_i, $i \in [1, v]$, a set of functions, some of which are non-linear in x_i.

Equations are divided in three sets, as follows:

(i) the accounting construction of price generation;

(ii) the accounting and behavioural equations that govern the four institutional sectors represented (households, firms, public administrations and the ‘rest of the world’);

(iii) the market clearing conditions

The full notation of variables and parameters (either calibrated on statistical data or exogenously) are found in in the end of this Annex.

AI.1 - Price system and income generation

The producer price of good *I*, $p_{Yi,}$ is built following the cost structure of the production of good i , that is as the sum of intermediate consumptions, labour costs, capital costs, land costs (for agriculture sectors only) a tax on production, and a constant mark-up rate (corresponding to the net operating surplus):

$$p_{Yi} = \sum_{j=1}^{n} p_{CIji}\, \alpha_{ji} + p_{Li}\, l_i + p_K\, k_i + p_{Ldi}\, ld_i + \overline{\tau_{Yi0}}\, p_{Yi} + \overline{\pi_{i0}}\, p_{Yi} \qquad \text{(eq. 1)}$$

Technical coefficients α_{ji} are expressed in physical units per unit of output according to the hybrid nature of the benchmark database.

For each sector, labour content is composed of low, medium and high skilled labour:

$$l_i = l_{il} + l_{im} + l_{ih} \qquad \text{(eq. 2)}$$

p_{Mi} the price of imported good i is good-specific. First, the international composite good is the *numéraire* of the model; its price is consequently assumed constant and equal to unity.

$$p_{MCOMP} = p_{MCOMP0} = 1 \qquad \text{(eq. 3)}$$

The prices of other imported goods evolve according to an exogenous assumption $\delta_{pMi \neq COMP}$:

$$p_{M_{i \neq COMP}} = \overline{\delta_{pM_{i \neq COMP}}} \, p_{M_{i \neq COMP}} \qquad \text{(eq. 4)}$$

p_i the average price of the resource of good i available on the domestic market is the weighted average of the two previous prices[77]:

$$p_i = \frac{p_{Yi} Y_i + p_{Mi} M_i}{Y_i + M_i} \qquad \text{(eq. 5)}$$

p_{CIij} the price of good i consumed in the production of good j is equal to the resource price of good i plus trade and transport margins, specific margins and a rate of excise taxes aggregate on consumption.

$$p_{CIij} = p_i \left(1 + \tau_{MCi} + \tau_{MTi} + \overline{\tau_{MSCIij0}} \right) \cdot \left(1 + \overline{\tau_{CONS_i 0}} \right) \qquad \text{(eq. 6)}$$

The consumer price of good i for households (p_{Ci}), public administrations (p_{Gi}) and investment (p_{Ii}), and the export price of good i (p_{Xi}), are constructed similarly:

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[77] The domestic and foreign varieties of the energy goods are indeed assumed homogeneous: the alternative assumption of product differentiation, adopted by many CGEM through their use of an Armington specification for international trade (ARMINGTON, 1969), has the disadvantage of creating ‘hybrid’ good varieties, whose volume unit is independent from that of the foreign and national varieties they hybridise; this forbids to maintain an explicit accounting of the physical energy flows and thus an energy balance. For the sake of simplicity the non-energy goods are treated similarly.

$$p_{Zi} = p_i \left(1 + \tau_{MCi} + \tau_{MTi} + \overline{\tau_{MSZi0}} \right) \cdot \left(1 + \overline{\tau_{CONS_i 0}} \right) \text{ with } Z \in \{C, G, I\} \qquad \text{(eq. 7)}$$

$$p_{Xi} = p_i \left(1 + \tau_{MCi} + \tau_{MTi} + \overline{\tau_{MSXi0}} \right) \qquad \text{(eq. 8)}$$

Before tax prices:

$$p_{BTCIij} = p_i \left(1 + \tau_{MCi} + \tau_{MTi} + \overline{\tau_{MSCIij0}} \right) \qquad \text{(eq. 9)}$$

$$p_{BTZi} = p_i \left(1 + \tau_{MCi} + \tau_{MTi} + \overline{\tau_{MSZi0}} \right) \text{ with } Z \in \{C, G, I, X\} \qquad \text{(eq. 10)}$$

Specific margins are calibrated at base year and held constant to reflect the difference of tariffs (taxes excluded) of energy goods according to the different consuming agent/sector.

Trade margins τ_{MCi} and transport margins τ_{MTi}, identical for all intermediate and final consumptions of good *i*, are calibrated at the reference equilibrium and kept constant—except those on transport sectors (LOAD + PASS = TRANS) and trade activities aggregated in the composite good (COMP), which are simply adjusted, in the reference equilibrium, to have the two types of margins sum up to zero:

$$\begin{aligned} &\sum_{j=1}^{n} \tau_{MTTRANS}\, p_{TRANS}\, \alpha_{TRANSj}\, Y_j + \tau_{MTTRANS}\, p_{TRANS} \left(C_{TRANS} + G_{TRANS} + I_{TRANS} + X_{TRANS} \right) \\ &+ \sum_{i \neq TRANS} \sum_{j} \overline{\tau_{MTi0}}\, p_i\, \alpha_{ij}\, Y_j + \sum_{i \neq TRANS} \overline{\tau_{MTi0}}\, p_i \left(C_i + G_i + I_i + X_i \right) = 0 \end{aligned} \qquad \text{(eq. 11)}$$

and similarly:

$$\sum_{j=1}^{n} \tau_{MCCOMP}\, p_{COMP}\, \alpha_{COMPj}\, Y_j + \tau_{MCCOMP}\, p_{COMP} \left(C_{COMP} + G_{COMP} + I_{COMP} + X_{COMP} \right)$$
$$+ \sum_{i \neq COMP} \sum_{j} \overline{\tau_{MCi0}}\, p_i\, \alpha_{ij}\, Y_j + \sum_{i \neq COMP} \overline{\tau_{MCi0}}\, p_i \left(C_i + G_i + I_i + X_i \right) = 0 \qquad \text{(eq. 12)}$$

Labour costs are equal to the sector specific net average wage w_i plus payroll taxes that correspond to employers social contributions for private and public employees pensions. They are levied based on average sector specific rates $\overline{\tau_{LTG_i}}$ and $\overline{\tau_{LTS_i}}$ calibrated at base year:

$$p_{Li} = \left(1 + \overline{\tau_{LG_i}} + \overline{\tau_{LS_i}} \right) w_i \qquad \text{(eq. 13)}$$

For each sector, the net representative wage is the average of the wages of the different labour skills:

$$w_i = \frac{l_{il} \cdot w_{il} + l_{im} \cdot w_{im} + l_{ih} \cdot w_{ih}}{l_i} \qquad \text{(eq. 14)}$$

For each type of skill $z \in \{l, m, h\}$ the wages w_{iz} in the different sectors vary homothetically:

$$w_{iz} = a_z \cdot w_{iz0} \qquad \text{(eq. 15)}$$

The average wage per skill of the total economy w_z is defined by:

$$w_z = \frac{\sum_{i=1}^{n} w_{iz}\, l_{iz}\, Y_i}{\sum_{i=1}^{n} l_{iz}\, Y_i} \qquad \text{(eq. 16)}$$

It is subject to variations that are either exogenised, or dictated by an assumption on the rate of unemployment per skill.

The cost of capital is understood as the cost of the 'machine' capital. It is obtained as the average price of investment goods.

$$p_K = \frac{\sum_{i=1}^{n} p_{Ii}\, I_i}{\sum_{i=1}^{n} I_i} \qquad \text{(eq. 17)}$$

AI.2 - Gross operating surplus

Trade-offs in the *i* productions, constant rates of operating margin π_i and specific margins τ_{MS} determine the gross operating surplus (*Excédent Brut d'Exploitation*, EBE) (land rents excluded):

$$EBE = \sum_{i=1}^{n} \left(p_{Ki}\, k_i\, Y_i + \overline{\pi_i}\, p_{Yi}\, Y_i \right) + M_S \qquad \text{(eq. 18)}$$

This *EBE*, which corresponds to capital income, is split between agents following constant shares (calibrated on the present equilibrium). By construction, the specific margins on the different sales M_S sum to zero in the base year equilibrium (this is a constraint of the hybridation procedure), however they do not in the future equilibrium, their constant rates being applied to varying prices. Their expression is then:

$$M_S = \sum_i \left(\sum_j \overline{\tau_{MSCI_{ij}}}\, p_i\, \alpha_{ij}\, Y_j + \sum_h \overline{\tau_{MSCh_i}}\, p_i\, C_{hi} + \overline{\tau_{MSG_i}}\, p_i\, G_i + \overline{\tau_{MSX_i}}\, p_i\, X_i \right) \qquad \text{(eq. 19)}$$

Sectors of agriculture use the specific factor of land and generate land income:

$$LAND = \sum_{i=1}^{n} p_{LDi}\, ld_i Y_i \qquad \text{(eq. 20)}$$

with $ld_i = 0$ for non-agricultural sectors. This land income is also split between agents following constant shares calibrated at base year.

AI.3 - Consumer price index

CPI the consumer price index is computed following Fisher, *i.e.* as the geometric mean of a Laspeyres index (variation of the cost of the present basket of goods from the present to the future set of relative prices) and a Paasche index (variation of the cost of the future basket of goods from the present to the future set of relative prices).

$$CPI = \sqrt{\frac{\sum_{i=1}^{n} p_{Ci}\, C_{i0}}{\sum_{i=1}^{n} p_{Ci0}\, C_{i0}} \frac{\sum_{i=1}^{n} p_{Ci}\, C_{i}}{\sum_{i=1}^{n} p_{Ci0}\, C_{i}}} \qquad \text{(eq. 21)}$$

AI.4 - Institutional sectors accounts

AI.4 .1- Households

The disaggregation of households into *m* classes (index *h*, $h \in [1, m]$) aims at taking into account income structures and eventually behaviours and adaptation capacities that can vary significantly among households.

AI.4 .1.1 - Demography:

The population of class *h*, N_h, grows from its reference value by exogenous δ_N percentage, common to all classes.

N_L is the total working population, N_{Lh} is the working population in class h, N_{Lz} is the total working population linked to labour type z and N_{Lzh} is the working population linked to labour type z in class h.

$$N_h = \left(1+\delta_N\right)^t N_{h0} \qquad \text{(eq. 22)}$$

AI.4.1.2 - Income formation, savings and investment decision

R_{DBAIh} the gross primary income of class h is defined as the sum of the following terms:

- Shares ω_{Lzh} of the total wage income per skill $\sum_{i=1}^{n} w_{iz} l_{iz} Y_i$ either calibrated at base year or corrected to reach desired Gini levels:

$$R_{Lh} = \sum_{z\in\{l,m,h\}} \left(\omega_{Lzh} \sum_{i=1}^{n} w_{iz} l_{iz} Y_i \right) \qquad \text{(eq. 23)}$$

- A share ω_{Kh} of the fraction of 'capital income' (the gross operating surplus of national accounting except 'land income') that goes to households, EBE_H. The ω_{Kh}'s are exogenous and their calibration is based on the benchmark SAM.
- A share ω_{LDh} of the fraction of 'land income' that goes to households $LAND_H$. The ω_{LDh}'s are exogenous and their calibration is based on the benchmark SAM.
- A 'debt service' -i_H D_h , which corresponds to property income (interests, dividends, real estate revenues, *etc.*). This service is the product of the households` net debt D_h, the evolution of which is explained below (eq. 41), and an endogenous effective interest rate i_H (eq. 41).
- Social transfers, in two aggregates (social transfers from public source ρ_{Gh} N_h and social transfers from private source ρ_{Sh} N_h) the calculation of which is similarly based on the product of a *per capita* income ρ and the population of each class. The population of class h, N_h, grows from its reference value by exogenous δ_N percentage (common to all classes).
- An exogenous share ω_{ATh} of residual transfers A_{TH} , which correspond to the sum of others transfers

Hence:

$$RDBAI_h = R_{Lh} + \overline{\omega_{Kh}}\, EBE_H + \overline{\omega_{LDh}}\, LAND_H - i_h\, D_h + \rho_{Gh}\, N_h + \rho_{Sh}\, N_h + \overline{\omega_{ATh}}\, A_{TH} \quad \text{(eq. 24)}$$

In particular, EBE_H, $LAND_{TH}$ and A_{TH} defined as constant shares ω_{KH}, ω_{LDH} and ω_{KH} of EBE (eq. 18), $LAND$ (eq. 21) and A_T (eq. 53):

$$EBE_H = \overline{\omega_{KH}}\, EBE \quad \text{(eq. 25)}$$

$$LAND_H = \overline{\omega_{LDH}}\, LAND \quad \text{(eq. 26)}$$

$$A_{TH} = \overline{\omega_{ATH}}\, A_T \quad \text{(eq. 27)}$$

The gross disposable income RDB_h of class h is obtained by subtracting from $RDBAI_h$ the income tax T_{IRh} levied at a constant average rate (eq. 41), and two other direct taxes T_{Gh} and T_{Sh} (respectively transferred to companies and government) that are indexed on CPI (eq. 21). R_h, the consumption budget of class h, is inferred from disposable income by subtracting savings. The savings rate τ_{Sh} is exogenous (calibrated to accommodate the values of RDB_h and R_h in the present equilibrium).

$$RDB_h = RDBAI_h - T_{IRh} - T_{Gh} - T_{Sh} \quad \text{(eq. 28)}$$

$$R_h = \left(1 - \overline{\tau_{Sh}}\right) RDB_h \quad \text{(eq. 29)}$$

A further exploration of the SAM data gives households\` investment $GFCF_h$ (Gross Fixed Capital Formation) as distinct from their savings; $GFCF_h$ is assumed to follow the simple rule of a fixed ratio to gross disposable income. The difference between savings and investment gives the self-financing capacity (SFC) of class h, CAF_h.

$$\frac{GFCF_h}{RDB_h} = \frac{GFCF_{h0}}{RDB_{h0}} \quad \text{(eq. 30)}$$

$$CAF_h = \overline{\tau_{Sh}} RDB_h - FBCF_h \quad \text{(eq. 31)}$$

The evolution of CAF_h between the present and future equilibrium can then be used to estimate the evolution of net debt D_h. The computation is based on the simple assumption that the average SFC over the years of projection t_{PROJ} is a mean of the present and future SFC.

$$D_h = D_{h0} - t_{PROJ} \frac{CAF_{h0} + CAF_h}{2} \quad \text{(eq. 32)}$$

AI.4.2 – Firms

AI.4.2.1 Gross disposable income and investment decision

Similar to that of households, the firms' disposable income RDB_S is defined as the sum of:

- an exogenous share ω_{KS} of capital income *i.e. EBE*
- an exogenous share ω_{LDS} of land income *i.e. LAND*
- a 'debt service' (interests, dividends) $-i_S D_S$, which is strongly negative in the present equilibrium (firms are net debtors in 2005), and served at an interest rate i_S that varies in the same way as i_H (eq. 66)
- two transfers linked to private social care: payroll tax $T_{LS} = \sum_{i=1}^{n} \overline{\tau_{LSi}} w_i l_i Y_i$ and the sum of other transfer from households $T_{Sh} = \overline{\tau_{Sh}} \cdot R_{Lh}$
- and an exogenous share ω_{ATS} of other transfers A_T, which are assumed a constant share of GDP

And the difference of:

- Total social transfers from private source R_S transferred to households that are the sum across household classes of the relative transfers defined as components of their before-tax disposable income $R_S = \sum_{h=1}^{m} \rho_{Sh} N_{Sh}$

- corporate tax payments T_{IS} payed to public administrations

Hence:

$$RDB_S = \overline{\omega_{KS}}\, EBE + \overline{\omega_{LDS}}\, LAND + T_{LS} + \sum_{h=1}^{m} T_{Sh} - i_S\, D_S + \overline{\omega_{ATS}}\, A_T - (R_S + T_{IS}) \qquad \text{(eq. 33)}$$

The ratio of the gross fix capital formation of firms $GFCF_S$ to their disposable income RDB_S is assumed constant; similar to households and in accordance with national accounting, their self-financing capacity CAF_S then arises from the difference between RDB_S and $FBCF_S$. The net debt of firms D_S is then calculated from their CAF_S following the same specification as that applied to households.

$$\frac{GFCF_S}{RDB_S} = \frac{GFCF_{S0}}{RDB_{S0}} \qquad \text{(eq. 34)}$$

$$CAF_S = RDB_S - FBCF_S \qquad \text{(eq. 35)}$$

$$D_S = D_{S0} - t_{PROJ}\, \frac{CAF_{S0} + CAF_S}{2} \qquad \text{(eq. 36)}$$

AI.4.3 - Public administration

AI.4.3.1 - Tax, social security contributions and fiscal policy

Tax and social security contributions form the larger share of government resources.

$$T_{LG} = \sum_{i=1}^{n} \overline{\tau_{LTGi}}\, w_i l_i Y_i \qquad \text{(eq. 37)}$$

$$T_Y = \sum_{i=1}^{n} \overline{\tau_{Y_i}}\, p_{Yi}\, Y_i \qquad \text{(eq. 38)}$$

$$T_{CONS} = \sum_{i=1}^{n} \left(\sum_{j=1}^{n} p_{BTCIij} \cdot \overline{\tau_{CONS_i}}\, \alpha_{ij}\, Y_j \right) + \overline{\tau_{CONS_i}} \left(p_{BTCi} \cdot C_i + p_{BTGi} \cdot G_i + p_{BTIi} \cdot I_i \right) \qquad \text{(eq. 39)}$$

$$T_{IS} = \overline{\tau_{IS}}\, EBE_S \qquad \text{(eq. 40)}$$

$$T_{IRh} = \overline{\tau_{IRh}}\, R_{DBAIh} \qquad \text{(eq. 41)}$$

$$T_{Gh} = \overline{\tau_{Gh}} \cdot R_{Lh} \qquad \text{(eq. 42)}$$

T is the sum of taxes and social contributions:

$$T = T_{LG} + T_Y + T_{CONS} + T_{IS} + \sum_{h=1}^{m} T_{IRh} + \sum_{h=1}^{m} T_{Gh} \qquad \text{(eq. 43)}$$

AI.4.3.2 - Gross disposable income, public spending, investment and transfers

Similar to households and firms (following the logic prevailing in the SAM), the gross disposable income of public administrations RDB_G is the sum of taxes and social contributions, of exogenous shares ω_{KG} of EBE, exogenous share ω_{LDG} of $LAND$ and ω_{ATG} of 'other transfers' A_T, and a debt service $i_G\, D_G$ from which are subtracted public expenditures $p_G\, G$ and social transfers R_h:

$$RDB_G = T + \overline{\omega_{KG}}\, EBE + \overline{\omega_{LDG}}\, LAND + \overline{\omega_{ATG}}\, A_T - i_G\, D_G - \left(\sum_{i=1}^{n} p_{Gi}\, G_i + R_G \right) \qquad \text{(eq. 44)}$$

Public expenditures $p_G\,G$ are assumed to keep pace with national income, and therefore are constrained as a constant share of GDP:

$$\frac{\sum_{i=1}^{n} p_{Gi}\,G_i}{PIB} = \frac{\sum_{i=1}^{n} p_{Gi0}\,G_{i0}}{PIB_0} \qquad \text{(eq. 45)}$$

Social transfers R_h are the sum across household classes of the transfers defined as components of their before-tax disposable income:

$$R_G = \sum_{h=1}^{m} \rho_{Gh}\,N_{Gh} \qquad \text{(eq. 46)}$$

For social transfers R_G and R_S, *per capita* transfers ρ_{Gh} and ρ_{Sh} are indexed on the average net wage:

$$\forall\ K \in [\mathrm{G, S}],\ \forall\ h \in [1,\mathrm{m}] \quad \rho_{Kh} = \frac{w}{w_0}\,\rho_{Kh0} \qquad \text{(eq. 47)}$$

At last, the interest rate i_G of public debt evolves as do i_H and i_S (eq. 66).

Public investment $GFCF_G$, same as public expenditures $pG\ G$, is supposed to mobilise a constant share of GDP. Subtracting it from RDB_G produces CAF_G, which determines the variation of the public debt:

$$\frac{FBCF_G}{PIB} = \frac{FBCF_{G0}}{PIB_0} \qquad \text{(eq. 48)}$$

$$CAF_G = RDB_G - FBCF_G \qquad \text{(eq. 49)}$$

$$D_G = D_{G0} - t_{PROJ}\,\frac{CAF_{G0} + CAF_G}{2} \qquad \text{(eq. 50)}$$

AI.4.4 - 'Rest of the world'

AI.4.4.1 - Capital flows and self-financing capacity

Capital flows from and to the 'Rest of the World' (ROW) are not assigned a specific behaviour, but are simply determined as the balance of capital flows of the three national institutional sectors (households, firms, public administrations) to ensure the balance of trade accounting. This assumption determines the self-financing capacity of ROW, which in turn determines the evolution of D_{RDM}, its net financial debt:

$$CAF_{RDM} = \sum_{i=1}^{n} p_{Mi} M_i - \sum_{i=1}^{n} p_{Xi} X_i + \sum_{K=H,S,G}^{n} i_K D_K - \sum_{K=H,S,G}^{n} A_{TK} \qquad \text{(eq. 51)}$$

$$D_{RDM} = D_{RDM\,0} - t_{PROJ} \frac{CAF_{RDM\,0} + CAF_{RDM}}{2} \qquad \text{(eq. 52)}$$

By construction the self-financing capacities (SFC) of the four agents clear (sum to zero), and accordingly the net positions, which are systematically built on the SFCs, strictly compensate each other in the projected as in the present equilibrium—indeed a nil condition on the sum of net positions could be substituted to **equation 52 (eq. 52)** without impacting the model. The assumption of a systematic 'compensation' by the ROW of the property incomes of national agents without any reference to its debt D_{RDM} may seem crude, but *in fine* only replicates the method of construction of the SAM. Indeed, in the 2005 calibration equilibrium the effective interest rate of the ROW (ratio of net debt to its property income), which ultimately results from a myriad of debit and credit positions and from the corresponding capital flows, is negative—unworkable for modelling purposes.

At last, as previously mentioned other transfers A_T («other current transfers» and «capital transfers») are defined as a fixed share of GDP:

$$\frac{A_T}{PIB} = \frac{A_{T0}}{PIB_0} \qquad \text{(eq. 53)}$$

AI.5 – Production and consumption trade-offs

AI.5.1 - Productive sectors trade-offs

The dual accounting framework of Imaclim-S concerning physical flows facilitates to embark bottom-up information in the GE framework for the representation of sectors production trade-offs. It makes it possible to depart from the classic method which consists in presupposing a functional form (like a CES) and calibrating it at base year using an assumption of optimality.

Practically, BU information can be embarked through two modalities:

- With a hard-linkage with a bottom-up model: in this case the macroeconomic production function which describes the choices of technical coefficients according to relative prices is replaced by a bottom-up model (ex: the production function of the power sector can be replaced by an optimization model specific to the power sector at the time horizon projected);
- With the calibration of a reduced form of a bottom-up model on pseudo-data as described by GHERSI AND HOURCADE (2006)

In the absence of specific bottom-up information, the production trade-offs, are limited by technical asymptotes that constrain the unit consumptions of factors above some floor values. Compared to GHERSI AND HOURCADE (2006), the restrictive assumption is made that the *variable* shares of the unit consumptions of factors (secondary inputs, labour and capital) are substitutable according to a CES specification—the existence of a fix share of each of these consumptions implies that the elasticities of substitution of *total* unit consumptions (sum of the fix and variable shares) are not fixed, but decrease as the consumptions approach their asymptotes.

Under these assumptions and constraints, the minimisation of unit costs of production leads to a formulation of the unitary consumptions of secondary factors α_{ji} , of labour l_i and of capital k_i which can be written as the sum of the floor value and a consumption above this value. The latter corresponds to the familiar expression of conditional factor demands of a CES production function with an elasticity of σ_i (the coefficients of which, λ_{CIij}, λ_{Li0} and λ_{Ki0}, are calibrated in the present equilibrium).

$$\alpha_{ji} = \frac{\Theta_i}{1+\phi_{ij}} \left[\beta_{ji}\, \alpha_{ji0} + \left(\frac{\lambda_{ji}}{p_{CIji}} \right)^{\sigma_i} \left(\sum_{j=1}^{n} \lambda_{ji}^{\ \sigma_i}\ p_{CIji}^{\ 1-\sigma_i} + \lambda_{Li}^{\ \sigma_i}\ p_{Li}^{\ 1-\sigma_i} + \lambda_{Ki}^{\ \sigma_i}\ p_K^{\ 1-\sigma_i} \right)^{-\frac{1}{\rho_i}} \right] \qquad \text{(eq. 54)}$$

$$l_i = \frac{\Theta_i}{1+\varphi_{li}} \left[\beta_{Li}\, l_{i0} + \left(\frac{\lambda_{Li}}{p_{Li}} \right)^{\sigma_i} \left(\sum_{j=1}^{n} \lambda_{ji}^{\ \sigma_i}\ p_{CIji}^{\ 1-\sigma_i} + \lambda_{Li}^{\ \sigma_i}\ p_{Li}^{\ 1-\sigma_i} + \lambda_{Ki}^{\ \sigma_i}\ p_K^{\ 1-\sigma_i} \right)^{-\frac{1}{\rho_i}} \right] \qquad \text{(eq. 55)}$$

$$k_i = \frac{\Theta_i}{1+\phi_{ki}} \left[\beta_{Ki}\, k_{i0} + \left(\frac{\lambda_{Ki}}{p_{Ki}} \right)^{\sigma_i} \left(\sum_{j=1}^{n} \lambda_{ji}^{\ \sigma_i}\ p_{CIji}^{\ 1-\sigma_i} + \lambda_{Li}^{\ \sigma_i}\ p_{Li}^{\ 1-\sigma_i} + \lambda_{Ki}^{\ \sigma_i}\ p_K^{\ 1-\sigma_i} \right)^{-\frac{1}{\rho_i}} \right] \qquad \text{(eq. 56)}$$

where for convenience

$$\rho_i = \frac{\sigma_i - 1}{\sigma_i} \qquad \text{(eq. 57)}$$

According to the exogenous growth framework of the model, this sum is modified to take into account the exogenous productivity improvements ϕ. It is also modified with an endogenous decreasing returns Θ_i. The latter impact all factor consumptions by assuming them elastic to the volume produced, by a fixed elasticity $\sigma_{\Theta Yi}$, which is calibrated under the assumption of marginal cost pricing.

$$\Theta_i = \left(\frac{Y_i}{Y_{i0}} \right)^{\sigma_{\Theta Yi}} \qquad \text{(eq. 58)}$$

$$\sigma_{\Theta Yi} = \frac{\overline{\pi_i}}{1-\overline{\pi_i}} \qquad \text{(eq. 59)}$$

Let us emphasise again that the 'cost of capital' p_K entering the trade-offs is *stricto sensu* the price of 'machine capital', *i.e.* equal to a simple weighted sum of the investment prices of immobilised goods (eq. 34), and unrelated to the interest rates charged on financial markets: on the one hand production trade-offs are based upon the strict cost of inputs, including that of physical capital k_i (calibrated on the consumption of fixed capital of the SAM); on the other hand, notwithstanding this arbitrage, the firms' activity and a rule of self-investment (eq. 34) lead to a change in their financial position D_S , whose service is not assumed to specifically weigh on physical capital as an input.

AI.5.2 - Household consumption choices

Household consumption C_{ih} is defined without any explicit utility function, as the sum of an exogenous basic need, common to all classes, and a consumption level above this floor, which varies according to a price elasticity σ_{CPi} and an income elasticity σ_{Cri}

$$\forall\ i \neq \text{COMP} \qquad C_{ih} = \beta_{ih}\, C_{ih0} + (1-\beta_{ih})\left(\frac{p_{Ci}}{IPC}\frac{1}{p_{Ci0}}\right)^{\sigma_{Cpi}}\left(\frac{R_h}{IPC}\frac{1}{R_{h0}}\right)^{\sigma_{CRi}} C_{ih0} \qquad \text{(eq. 60)}$$

Where COMP represents the production of the Composite sector, and β_{ih} represents the share of class h relative to the basic need (arbitrarily defined as 70% of the lowest household consumption level in base year).

In this thesis, an alternative approach to defining household consumption is applied, as an attempt to represent Engel curves (see section 3.7) in household budget.

$$\forall\ i \neq \text{COMP} \qquad C_{ih} = \iota_{ih} R_h \qquad \text{(eq. 61)}$$

It is defined by the product of ι_{ih}, budget share of good *i* for household *h*, and R_h, the income allocated in consumption.

C_{COMPh} corresponds to the demand for Composite goods and services, simply defined by deducting consumption from all sectors from the household`s consumption income.

$$p_{CCOMP}\, C_{COMPh} = R_h - p_{ih}\, C_{ih} \qquad \text{(eq. 62)}$$

Combining this formulation with equation 61 (eq. 61) guarantees that the adding-up principle is met – the sum of shares of all goods must equal to 1.

AI.6 - Trade

Competition on international markets is settled through relative prices. The ratio of imports to domestic production on the one hand, and the 'absolute' exported quantities on the other hand, are elastic to the terms of trade, according to constant, product-specific elasticities:

$$\frac{M_i}{Y_i} = \frac{M_{i0}}{Y_{i0}} \left(\frac{p_{Mi0}}{p_{Yi0}} \frac{p_{Yi}}{p_{Mi}} \right)^{\sigma_{Mpi}} \qquad \text{(eq. 63)}$$

$$\frac{X_i}{X_{i0}} = \left(\frac{p_{Mi0}}{p_{Xi0}} \frac{p_{Xi}}{p_{Mi}} \right)^{\sigma_{Xpi}} \left(1 + \delta_{Xi}\right) \qquad \text{(eq. 64)}$$

The different treatment of imports and exports merely reflects the assumption that, notwithstanding the evolution of the terms of trade, import volumes rise in proportion to domestic economic activity (domestic production), while exports do not. Exports are however impacted by global growth, independently of terms of trade variations. This is captured by assuming an extra, exogenous δ_{Xi} increase of volumes exported.

Total exports are then determined by a terms-of-trade elastic share of a δ_{Xi} expanded international market.

AI.7 - Market balances

AI.7.1 - Goods markets

Goods market clearing is a simple accounting balance between resources (production and imports) and uses (households and public administrations' consumption, investment, exports).

$$Y_i + M_i = C_i + G_i + I_i + X_i \qquad \text{(eq. 65)}$$

AI.7.2 - Investment and capital flows

The effective interest rates i_H , i_S and i_G faced by households, firms and public administrations, settle to balance capital markets: their shift from a common point differential δ_i (eq. 66) impacts the households` and firms' disposable incomes RDB_H and RDB_S, hence their investment decisions $FBCF_H$ and $FBCF_S$, in order to match the supply of capital they correspond to, adding up to the public GFCF $FBCF_G$, to the demand for investment goods $p_{Ii}\, I_i$ (eq. 67). This demand is in turn constrained by the assumption that the ratio of each of its real components I_i to total fixed capital consumption (the sum of $k_i\, Y_i$) is constant. In other words, the capital immobilised in all productions is supposed homogeneous, and all its components vary as the total consumption of fixed capital.

$$\forall\ K \in [H, S, G] \qquad i_K = i_{K0} + \delta_i \qquad \text{(eq. 66)}$$

$$\sum_{K=H,S,G} FBCF_K = \sum_{i=1}^{n} p_{Ii}\, I_i \qquad \text{(eq. 67)}$$

$$\frac{I_i}{\sum_{j=1}^{n} k_j\, Y_j} = \frac{I_{i0}}{\sum_{j=1}^{n} k_{j0}\, Y_{j0}} \qquad \text{(eq. 68)}$$

Therefore the closure of the model is fundamentally made on the investment supply of agents, which mechanically adapts to the investment demand from productions. Through an adjustment of interest rates it leads to fluctuations in financial flows between creditors and debtors, and eventually in some evolution of their net financial positions. In most versions of the model, where the budgetary option retained for public accounts implies some control of the debt, a feedback effect is obtained through the necessary adjustment of the taxes pinpointed as control variables (social contributions in the central assumption of an environmental fiscal reform partially substituting a carbon tax to them).

AI.7.3 - Labour market

The labour market results from the interplay of labour demand from the production systems, equal to the sum of their factor demands $l_i\, Y_i$, and of labour supply from households. The labour endowment of households L_0 grows by an exogenous, common rate δ_L for all classes, calibrated on the total full-time equivalent of the active population in the present and future equilibrium. However the model allows for a strictly positive unemployment rate u and the market clearing condition writes:

$$(1-u_z)(1+\delta_{Lz})\sum_{h=1}^{m} N_{Szh} = \sum_{i=1}^{n} l_{iz}\, Y_i \qquad \text{(eq. 69)}$$

Rather than explicitly describing labour supply behaviour, the model alternatively treats as exogenous the overall unemployment rate u, or δw the growth of the average real wage w:

$$u_z = \overline{u_z} \quad \text{(eq. 70)}$$

AI.8 Variables

α_{ij}	Technical coefficient, quantity of good *i* entering the production of one good *j*
A_T	Other transfers (equivalent of accounts D7 and D9 of the TEE)
A_{TH}	Other transfers to the households
A_{TS}	Other transfers to firms
A_{TG}	Other transfers to the public administrations
CAF_H	Self-financing capacity of class *h*
CAF_S	Self-financing capacity of firms
CAF_G	Self-financing capacity of the public administrations
CAF_{RDM}	Self-financing capacity of the rest of the world
C_{ih}	Final consumption of good *i* by household class *h*
D_h	Net debt of class *h* Calibrated on the net financial assets (*patrimoine financier net*) of the INSEE *Comptes de patrimoine*
D_S	Net debt of firms Calibrated on the net financial assets (*patrimoine financier net*) of the INSEE *Comptes de patrimoine*
D_G	Net public debt Calibrated on the net financial assets (*patrimoine financier net*) of the INSEE *Comptes de patrimoine*
D_{RDM}	Net debt of the rest of the world Calibrated on the net financial assets (*patrimoine financier net*) of the INSEE *Comptes de patrimoine*
δ_i	Reform-induced interest rate differential
EBE_H	Gross operating surplus accruing to households

EBE_S	Gross operating surplus accruing to firms
EBE_G	Gross operating surplus accruing to public administrations
$FBCF_h$	Gross fixed capital formation of household class *h*
$FBCF_S$	Gross fixed capital formation of firms
$FBCF_G$	Gross fixed capital formation of administrations publiques
γ_{CIij}	CO_2 emissions per unit of good *i* consumed in the production of good *j*
γ_{CFi}	CO_2 emissions per unit of good *i* consumed by households
G_i	Final public consumption of good *i*
i_H	Effective interest rate on the net debt of ménages
i_S	Effective interest rate on the net debt of sociétés
i_G	Effective interest rate on the net debt of administrations publiques
I_i	Final consumption of good *i* for the investment
IPC	Consumer price index (Fisher)
k_i	Capital intensity of good *i*
l_i	Labour intensity of good *i*
ω_{Lh}	Share of labour income accruing to household class *h*
M_i	Imports of good *i*
M_S	Sum across goods and uses of the specific sale margins
N_{Lh}	Employed population of household class *h* (full time equivalent)
p_{Mi}	Import price of good *i*
p_i	Average price of the resource in good *i* (domestically produced and imported)
p_{CIij}	Price of good *i* for the production of good *j*

p_{Ci} Consumption price of good *i*

p_{Gi} Public price of good *i*

p_{Ii} Investment price of good *i*

Φ_i Endogenous technical progress coefficient applying to the production of good *i*

p_K Cost of capital input (weighted sum of investment prices)

p_{Li} Cost of labour input in the production of good *i*

p_{Xi} Export price of good *i*

p_{Yi} Production price of good *i*

R_{DBAIh} Before-tax gross disposable income of household class *h*

R_{DBH} Gross disposable income of household class *h*

R_{DBS} Gross disposable income of sociétés

R_{DBG} Gross disposable income of administrations publiques

R_h Consumed income of household class *h*

R_A Social transfers to households not elsewhere included

R_U Sum of unemployment benefits

R_S Sum of retirement pensions

ρ_{Ah} Average *per capita* not-elsewhere-included transfers of household class *h*

ρ_{Ph} Average *per capita* pensions of household class *h*

ρ_{Uh} Average *per capita* unemployment benefits of household class *h*

$\sigma_{\Theta i}$ Elasticity of the decreasing returns coefficient of production *i* to its output.

T Total taxes and social contributions

T_{CS} Sum of social contributions of the employer and the employee

T_{TIPP} Fiscal revenues from the 'internal tax on petroleum products (*Taxe Intérieure sur les Produits Pétroliers*, TIPP)

T_{AIP} Fiscal revenues of excise taxes other than the TIPP

T_{TVA} VAT revenues

T_{IS} Corporate tax revenues

T_{IRh} Household class h income tax payments

T_h Other direct taxes paid by household class h

T_{CARB} Carbon tax revenues

Θ_i Decreasing returns coefficient for the production of good i

τ_{CS} Social contribution rate applicable to net wages

τ_{MCCOM} Commercial mark-up on the commercial good or on the aggregate encompassing it

$\tau_{MCTRANS}$ Transport mark-up on the transport good or on the aggregate encompassing it

U Unemployment rate

u_h Household class h unemployment rate

w_i Average net wage in the production of good i

W Average net wage across productions

X_i Good i exports

Y_i Good i production

AI.9 Parameters calibrated on statistical data

$\overline{L}$ Total active population in full-time equivalents (INSEE data)

$\overline{L_h}$ Active population of household class *h* in full-time equivalents. Calibrated by applying to total *L* the shares of active population drawn from the *m*-class aggregation of the 10305 households of the *Budget de Famille* 2001 survey by INSEE.

λ_{ij}, λ_{Li}, λ_{Ki} Coefficients of the CES production function governing the variables shares of conditional factor demands. Calibrated on the first order conditions of cost minimisation applied to the no-policy equilibrium (functions of prices p_{CIij0} , p_{Li0} and p_{Ki0} , of quantities α_{ij0} , l_{i0} et k_{i0} , and of basic need shares β_{ij} , β_{Ki} et β_{Li}).

$\overline{N_h}$ Total population of household class *h*. Calibrated by applying to total 2004 population the shares of total population drawn from the *m*-class aggregation of the 10305 households of the *Budget de Famille* 2001 survey by INSEE.

$\overline{N_{Ph}}$ Number of retirees of household class *h*. Calibrated by applying to the 2004 retiree population the shares of retiree population drawn from the *m*-class aggregation of the 10305 households of the *Budget de Famille* 2001 survey by INSEE.

$\overline{\omega_{ATh}}$ Share of the other transfers accruing to households devoted to household class *h*. Calibrated as the share accruing to household class *h* of revenues other than those of labour, in the *m*-class aggregation of the 10305 households of the *Budget de Famille* 2001 survey by INSEE.

$\overline{\omega_{ATH}}$ Share of other transfers accruing to households (all classes together). Calibrated on the TEE.

$\overline{\omega_{ATS}}$ Share of other transfers accruing to firms. Calibrated on the TEE (aggregate of financial and non-financial firms, and of non-profit organisations).

$\overline{\omega_{ATG}}$ Share of other transfers accruing to public administrations. Calibrated on the TEE.

$\overline{\omega_{Kh}}$ Share of the capital income of households accruing to household class *h*. Calibrated as the share accruing to household class *h* of revenues other than those of labour, in the *m*-class aggregation of the 10305 households of the *Budget de Famille* 2001 survey by INSEE.

$\overline{\omega_{KH}}$ Share of capital income accruing to households (all classes). Calibrated on the TEE.

$\overline{\omega_{KS}}$ Share of capital income accruing to firms. Calibrated on the TEE (aggregate of financial and non-financial firms, and of non-profit organisations).

$\overline{\omega_{KG}}$ Share of capital income accruing to public administrations. Calibrated on the TEE

$\overline{\pi_i}$ Mark-up rate (rate of net operating surplus) in the production of good *i*. Calibrated as the ratio of net operating surplus to distributed output (TES and more broadly INSEE data).

$\overline{t_{AIPi}}$ Excise taxes other than the TIPP per unit of consumption of good *i*. Calibrated as the ratio of the corresponding fiscal revenue of each good *i* (TES data after subtraction of the TIPP) to total domestic consumption in the no-policy equilibrium $Y_{i0} + M_{i0} - X_{i0}$ (exports are assumed to be exempted).

$\overline{t_{TIPPCFi}}$ TIPP per TOE of automotive fuel of household consumption. The TIPP is isolated from other excise taxes and split between goods GG15 and GG2B of the TES: refined petroleum products and natural gas. The split between TIPP on intermediate *vs.* final sales is calibrated on data from the *Comité Professionnel Du Pétrole* (CPDP).

$\overline{t_{TIPPCIi}}$ TIPP per TOE of automotive fuel of intermediate consumption. The TIPP is isolated from other excise taxes and split between goods GG15 and GG2B of the TES: refined petroleum products and natural gas. The split between TIPP on intermediate *vs.* final sales is calibrated on data from the *Comité Professionnel Du Pétrole* (CPDP).

$\overline{\tau_{IRh}}$ Effective income tax rate of household class *h*. Calibrated as the ratio of income tax payments to the before-tax gross disposable income. Both aggregates are distributed among household classes based on the shares observed in the *m*-class aggregation of the 10305 households of the *Budget de Famille* 2001 survey by INSEE.

$\overline{\tau_{IS}}$ Effective corporate tax rate. Calibrated as the ratio of the corporate tax fiscal revenue, to the share of the gross operating surplus accruing to firms.

$\overline{\tau_{MSCIij}}$ Specific mark-up rate on intermediate energy consumptions (if *i* is not an energy good then the rate is nil). Defined during the hybridisation procedure.

$\overline{\tau_{MSCi}}$ Specific mark-up rate on household energy consumptions (if *i* is not an energy good then the rate is nil). Defined during the hybridisation procedure

$\overline{\tau_{MSGi}}$ Specific mark-up rate on public energy consumptions (if *i* is not an energy good then the rate is nil). Defined during the hybridisation. Under the convention that public energy consumptions are nil this parameter is pointless.

$\overline{\tau_{MSXi}}$ Specific mark-up rate on energy exports (if *i* is not an energy good then the rate is nil). Defined during the hybridisation procedure

$\overline{\tau_{Sh}}$ Savings rate of household class *h*. Calibrated as the ratio of the savings of class h to its gross disposable income, with the data being derived from all the main data sources (TES, TEE, data from the *Budget de Famille* survey aggregated in *m* classes).

$\overline{\tau_{TVAi}}$ VAT rate applying to the final consumption of good *i*. Calibrated on TES data by treating the VAT as a simple sales tax levied indifferently on *C*, *G* and *I*.[78]

AI.10 Exogenous parameters

β_{ih} Share of the good *i* consumption of household class *h* that corresponds to a basic need. Set for each good *i* at a level that defines a basic need equal to 80% of the real consumption of the class for which it is the lowest.

β_{ji} Technical asymptote of the technical coefficient α_{ji}.

β_{Ki} Technical asymptote of the capital intensity of good *i*.

[78] In the TES investment is conventionally valued at prices that include the VAT. Treating the VAT as a sales tax cancels some distributive effects between productions, all the more negligible as the good aggregation is high. In most policy runs it is virtually without discernable effect on macroeconomic results or those concerning the distribution of income between households.

β_{Li}	Technical asymptote of the labour intensity of good *i*.
ι_{ih}	Budget share of good *i* for household *h*
σ	Substitution elasticity of the variable shares of production factors.
σ_{Cri}	Income-elasticity of household consumption of good *i*. An econometric estimate over aggregate 1985-2006 data.
σ_{Cpi}	Price-elasticity of household consumption of good *i*. An econometric estimate over aggregate 1985-2006 data.
σ_{Mpi}	Elasticity of the ratio of imports to domestic production of good *i*, to the corresponding terms of trade.
$\sigma_{\Phi i}$	Elasticity of the technical progress coefficient of production *i* to its fixed capital consumption (whose variations are taken as a proxy of those of cumulated investment).
σ_{Xpi}	Elasticity of good *i* exports to the corresponding terms of trade.
σ_{wu}	Elasticity of the average net wage (nominal or real, *cf. supra*) to the unemployment rate.
t_{CI}	Carbon tax on the carbon emissions of intermediate consumptions.
t_{CF}	Carbon tax on the carbon emissions of household consumptions.
t_{REF}	Time of development of the reform (years).

Annex II – Supplement to Chapters 4 and 5 (Reconciliation between Imaclim-S BR sectors and POF categories, subsidies on scenarios` assumptions)

Table AII.1 - Consumption expenditures reconciliation

Imaclim-S BR sectors	POF categories
Biomass	Álcool - veículo próprio
Coal	n/a
Oil	n/a
Natural Gas	Gás doméstico
Oil products	Gasolina - veículo próprio
Electricity	Energia elétrica
Construction	n/a
Transportation - Load	idem "Despesas diversas"
Transportation - Passenger	Urbano
Livestock	Carnes, vísceras e pescados
Agriculture and agroindustry	"Alimentação no domicilio"
Paper	Periódicos, livros, revistas Livros e revistas técnicas
Cement	Imóvel reforma
Steel	n/a
Non-Ferrous metals	n/a
Chemicals	Produtos de higiene Artigos de limpeza Remédios
Mining	idem "Cement"
Rest of Industry	Manutenção do lar Mobiliários e artigos do lar Eletrodomésticos

	Água e esgoto Vestuário Manutenção e acessórios Aquisição de veículos Artigos escolares Material de tratamento Brinquedos e jogos Celular e acessórios Fumo
Composite (Services)	Alimentação fora do domicílio Aluguel Condomínio Telefone celular Telefone fixo Pacote de telefone Consertos de artigos do lar Outros (serviços e taxas) Serviços pessoais Viagens esporádicas Outras (transporte) Cursos regulares Curso superior Outros cursos e atividades Outras (educação) Plano/Seguro saúde Consulta médica Consulta e tratamento dentário Tratamento médico e ambulatorial Serviços de cirurgia

	Hospitalização Exames diversos Outras (assistência à saúde) Recreações e esportes Outras (recreação e cultura) Serviços bancários Despesas diversas

Table AII.2 - Other expenditures (non-consumption) reconciliation

Imaclim-S BR categories	POF categories
THS (contribution for private care) THP (contribution for public care) TIR (tax on income) CAFH (operating cash flow)	Previdência privada Contribuições trabalhistas Impostos
GFCFH (Gross fixed capital formation)	Imóvel (aquisição) Prestação de imóvel Outros investimentos Imóvel reforma

Table AII.3 - Income sources and transfers among agents reconciliation

Imaclim-S BR categories	POF categories
Ldn (Domestic national wages)	Rendimento do trabalho Empregado Empregador Conta própria
KH (Income from productive capital)	Aplicações de capital
LaH (Land rent)	Aluguel de bens imóveis
PiH (Redistributed profits)	Aplicações de capital
RK (Net financial income)	Rendimento de aluguel
MH (margins)	Aplicações de capital
RSH (Private social transfers)	Previdência privada
RGH (Public social transfers)	Prev. publica
AT (Other transfers)	Bolsa de estudo Pensão, mesada, doação Transferências transitórias Vendas esporádicas Empréstimos Outros rendimentos
Transfers among households	Pensões mesadas e doações

Table AII.4 – Greenhouse gases emissions results from IES-Brasil 2050 Governmental Plan Scenario

	2005	2050
Energy	317	601
AFOLU	1,621	110
IPPU	80	192
Waste	60	184
Total	**2,077**	**1,088**

Source: LA ROVERE et al. (2017)

Table AII.5 - Composition for average and healthy diets by product category (grams per day per capita) and variation (%)

	Average	Healthy	Variation (%)
Bread & cereals	208	329	58%
Fruits & Vegetables	504	776	54%
Poultry	32	7	-79%
Other meats	87	28	-68%
Beef	47	19	-61%
Fish & Seafood	30	29	-1%
Animal products	154	154	0%
Oils and fats	15	21	39%
Beverages	n.d.	n.d.	-20% (arbitrarily defined)
Other foods	364	245	-33%
Total (g/day)	**1,441**	**1,607**	**12%**

Annex III – Comparison between Reference scenario and preliminary assessment – Income, consumption and direct household energy GHG emissions levels

This annex compares household results for the reference scenario using two different demand functions:

(a) using income elasticities econometrically calibrated on past data, which is the approach used in the preliminary assessment to identify household income evolution explained in section 5.3.1.3 (Table 5.6 - Preliminary assessment of real consumption income evolution (R$2005) and definition of benchmark for 2050 consumption structure);

(b) using Engel Curves to define household preferences according to the level of income in 2050 derived from the preliminary assessment, which is the approach used in the reference scenario (REF).

Table AIII.1 presents the energy-related emissions variation for household classes using both approaches. Tables AIII.2 to AIII.4 detail consumption levels 2005 and 2050 (Table AIII.4 also compares REF levels to those from the preliminary assessment in terms of percentual variation). For similar levels of household income in the preliminary assessment and the reference scenario, energy emissions from classes HH1 to HH4 increase less than in REF, for leaps in consumption are not captured. Income elasticities are calculated over very low consumption levels for private vehicles fuels and electricity. In contrast, demand for public transportation is overestimated. Conversely, energy emissions for HH5 and HH6 are higher, since their consumption of oil products, for example, soars because income elasticities cannot foresee whether consumption saturates after a given threshold. Saturation also explains the reason why food consumption is lower for all classes in REF than in the preliminary assessment. Section 3.7 discusses these aspects in more detail. The comparison between the two alternatives evidences that the use of Engel curves opted for in this thesis provides a more realistic consumption profile in 2050.

Table AIII.1 – Comparison of households` energy emissions variation from 2005 to 2050 (%) - Preliminary assessment vs. REF

	2050	
	Preliminary assessment	**REF**
HH1	628%	1639%
HH2	503%	953%
HH3	390%	518%
HH4	317%	460%
HH5	263%	240%
HH6	246%	121%
National average	**135%**	**270%**

Table AIII.2 – Per capita income and consumption levels per class in 2005

	HH1	**HH2**	**HH3**	**HH4**	**HH5**	**HH6**
Real per capita consumption income (R$2005)	2,216	3,227	4,824	7,099	11,672	26,423
Biomass (toe)	0.05	0.05	0.06	0.07	0.08	0.11
Natural Gas (toe)	0.00	0.00	0.00	0.00	0.00	0.00
Oil products (toe)	0.01	0.01	0.03	0.07	0.17	0.44
Electricity (toe)	0.01	0.02	0.03	0.04	0.06	0.10
Public transportation (thousand pass.km)	0.92	1.40	2.04	2.88	4.23	8.63
Agriculture and agroindustry (R$2005)	0.58	0.72	0.87	1.10	1.29	2.00
Energy intensive industry (R$2005)	0.11	0.17	0.23	0.35	0.50	0.96
Rest of Industry (R$2005)	0.18	0.28	0.46	0.76	1.46	3.44

Services (R$2005)	1.00	1.59	2.63	3.95	7.04	17.51

Table AIII.3 – Per capita income and consumption levels per class in preliminary assessment

	HH1	**HH2**	**HH3**	**HH4**	**HH5**	**HH6**
Real per capita consumption income (R$2005)	9,410	12,727	14,776	20,960	29,946	67,830
Biomass (toe)	0.21	0.19	0.20	0.23	0.23	0.32
Natural Gas (toe)	0.00	0.01	0.01	0.01	0.01	0.01
Oil products (toe)	0.04	0.06	0.10	0.22	0.50	1.25
Electricity (toe)	0.05	0.07	0.08	0.11	0.15	0.24
Public transportation (thousand pass.km)	4.86	6.38	6.49	8.49	11.14	22.50
Agriculture and agroindustry (R$2005)	2.42	2.58	2.61	2.76	2.96	4.39
Energy intensive industry (R$2005)	0.32	0.48	0.59	0.87	1.14	2.18
Rest of Industry (R$2005)	0.54	0.81	1.16	1.83	3.28	7.59
Services (R$2005)	4.79	7.31	8.68	13.20	19.08	47.31

Table AIII.4 – Per capita income and consumption levels per class in REF and variation relative to preliminary assessment (%)

	HH1	HH2	HH3	HH4	HH5	HH6
Real per capita consumption income (R$2005)	9,353 (-1%)	12,646 (-1%)	15,223 (+3%)	21,537 (+3%)	29,711 (-1%)	62,500 (-8%)
Biomass (toe)	0.21 (0%)	0.22 (+17%)	0.23 (+15%)	0.24 (+2%)	0.23 (-1%)	0.24 (-25%)
Natural Gas (toe)	0.01 (+148%)	0.01 (+98%)	0.01 (+63%)	0.02 (+162%)	0.02 (+137%)	0.02 (+112%)
Oil products (toe)	0.08 (+138%)	0.10 (+73%)	0.13 (+24%)	0.29 (+31%)	0.46 (-8%)	0.78 (-37%)
Electricity (toe)	0.05 (+17%)	0.07 (-3%)	0.08 (0%)	0.11 (+4%)	0.14 (-6%)	0.19 (-21%)
Public transportation (thousand pass.km)	4.20 (-14%)	5.08 (-20%)	6.12 (-6%)	8.66 (+2%)	10.64 (-4%)	14.02 (-38%)
Agriculture and agroindustry (R$2005)	1.46 (-40%)	1.68 (-35%)	2.03 (-22%)	2.01 (-27%)	2.26 (-24%)	2.27 (-48%)
Energy intensive industry (R$2005)	0.50 (+56%)	0.60 (+24%)	0.72 (+22%)	1.01 (+16%)	1.17 (+2%)	1.62 (-26%)
Rest of Industry (R$2005)	1.11 (+106%)	1.75 (+117%)	2.11 (+82%)	2.99 (+64%)	4.30 (+31%)	5.45 (-28%)
Services (R$2005)	4.91 (+3%)	7.01 (-4%)	8.45 (-3%)	12.87 (-2%)	18.68 (-2%)	50.32 (+6%)

Annex IV - Detailed Numerical Results

Table AIV.1 – Nominal wages (thousand R$)

	2005	2050		
	Base year	**REF**	**LES**	**LES-Tr**
Biomass	0.9	1.0	1.1	1.3
Coal	8.1	9.0	9.5	11.4
Oil	101.2	112.4	118.9	142.6
Natural Gas	79.6	88.4	93.5	112.2
Oil products	16.4	18.2	19.3	23.1
Electricity	30.4	33.8	35.8	42.9
Public transportation	10.8	11.9	12.6	15.2
Livestock	9.0	10.0	10.5	12.6
Agriculture and agroindustry	3.9	4.3	4.5	5.4
Energy intensive industry	20.4	22.6	23.9	28.7
Rest of Industry	8.6	9.5	10.1	12.1
Services	10.3	11.5	12.1	14.5

Table AIV.2 – Real wages (thousand R$2005)

	2005	2050		
	Base year	**REF**	**LES**	**LES-Tr**
Biomass	0.9	1.0	0.9	1.0
Coal	8.1	8.5	8.3	8.7
Oil	101.2	105.9	103.4	108.4
Natural Gas	79.6	83.3	81.3	85.3
Oil products	16.4	17.2	16.7	17.6
Electricity	30.4	31.8	31.1	32.6
Public transportation	10.8	11.2	11.0	11.5
Livestock	9.0	9.4	9.2	9.6
Agriculture and agroindustry	3.9	4.0	4.0	4.1
Energy intensive industry	20.4	21.3	20.8	21.8
Rest of Industry	8.6	9.0	8.8	9.2
Services	10.3	10.8	10.5	11.1

Table AIV.3 - Labour intensity variation and capital intensity variation, relative to base year (%)

	Labour intensity variation (%)			Capital intensity variation (%)		
	REF	**LES**	**LES-Tr**	**REF**	**LES**	**LES-Tr**
Biomass	-61.3%	-61.6%	-61.6%	15.3%	14.5%	14.5%
Coal	-61.6%	-61.6%	-61.6%	14.5%	14.5%	14.5%
Oil	-61.6%	-61.6%	-61.6%	14.5%	14.5%	14.5%
Natural Gas	-61.6%	-61.6%	-61.6%	14.5%	14.5%	14.5%
Oil products	-61.6%	-61.6%	-61.6%	14.5%	14.5%	14.5%
Electricity	-61.6%	-61.6%	-61.6%	14.5%	14.5%	14.5%
Public transportation	-61.6%	-61.6%	-61.6%	14.5%	14.5%	14.5%
Livestock	-61.6%	-61.6%	-61.6%	14.5%	14.5%	14.5%
Agriculture and agroindustry	-61.7%	-61.6%	-61.6%	14.4%	14.5%	14.5%
Energy intensive industry	-61.6%	-61.6%	-61.6%	14.5%	14.5%	14.5%
Rest of Industry	-61.8%	-61.6%	-61.6%	14.1%	14.5%	14.5%
Services	-61.7%	-61.6%	-61.7%	14.4%	14.5%	14.8%

Table AIV.4 – Nominal consumer prices variation relative to base year (%)

	REF	LES	LES-Tr
Biomass	-12%	-7%	7%
Coal	7%	8%	11%
Oil	19%	25%	41%
Natural Gas	6%	11%	20%
Oil products	12%	18%	33%
Electricity	9%	15%	29%
Public transportation	-7%	0%	15%
Livestock	5%	13%	31%
Agriculture and agroindustry	5%	16%	30%
Energy intensive industry	-2%	2%	13%
Rest of Industry	-5%	-1%	10%
Services	12%	21%	40%

Table AIV.5 – Real per capita expenditure with biomass per class (R$2005)

	2005		2050	
	Base year	REF	LES	LES-Tr
HH1	44	160	159	167
HH2	50	168	167	174
HH3	56	174	172	179
HH4	68	181	180	187
HH5	74	174	173	179
HH6	102	184	184	189

Table AIV.6 – Real per capita expenditure with natural gas per class (R$2005)

	2005	2050		
	Base year	**REF**	**LES**	**LES-Tr**
HH1	1	9	8	8
HH2	1	9	8	8
HH3	2	9	8	8
HH4	2	16	14	15
HH5	2	15	13	13
HH6	2	14	13	13

Table AIV.7 – Real per capita expenditure with oil products per class (R$2005)

	2005	2050		
	Base year	**REF**	**LES**	**LES-Tr**
HH1	15	227	135	141
HH2	30	276	145	151
HH3	65	344	172	179
HH4	165	781	345	358
HH5	426	1,231	528	547
HH6	1,117	2,108	863	889

Table AIV.8 – Real per capita expenditure with electricity per class (R$2005)

	2005	2050		
	Base year	**REF**	**LES**	**LES-Tr**
HH1	39	194	165	173
HH2	63	238	200	209
HH3	106	285	240	249
HH4	149	414	342	355
HH5	216	504	415	430
HH6	348	686	565	581

Table AIV.9 – Real per capita expenditure with public transportation per class (R$2005)

	2005	2050		
	Base year	**REF**	**LES**	**LES-Tr**
HH1	108	433	413	432
HH2	164	523	497	518
HH3	239	630	596	620
HH4	337	892	840	873
HH5	496	1,096	1,025	1,061
HH6	1,011	1,444	1,312	1,351

Table AIV.10 – Real per capita expenditure with food per class (R$2005)

	2005		2050	
	Base year	REF	LES	LES-Tr
HH1	747	1,866	1,747	1,827
HH2	937	2,146	1,986	2,071
HH3	1,132	2,596	2,367	2,463
HH4	1,431	2,567	2,281	2,369
HH5	1,668	2,890	2,536	2,626
HH6	2,589	2,904	2,618	2,695

Table AIV.11 – Real per capita expenditure with other goods per class (R$2005)

	2005		2050	
	Base year	REF	LES	LES-Tr
HH1	377	1,893	1,459	1,526
HH2	577	2,753	2,028	2,114
HH3	898	3,318	2,436	2,534
HH4	1,443	4,694	3,308	3,435
HH5	2,555	6,407	4,412	5,241
HH6	5,737	8,292	5,674	5,841

Table AIV.12 – Real per capita expenditure with services per class (R$2005)

	2005		2050	
	Base year	REF	LES	LES-Tr
HH1	887	4,569	5,112	5,345
HH2	1,405	6,533	7,384	7,698
HH3	2,327	7,866	8,940	9,303
HH4	3,504	11,991	13,790	14,322
HH5	6,236	17,395	19,961	20,003
HH6	15,516	46,868	50,202	51,677

Table AIV.13 – Gross exports to sectoral GDP ratio and gross imports to sectoral GDP ratio (%)

	Gross exports to sectoral GDP ratio (%)				Gross imports to sectoral GDP ratio (%)			
	2005	2050			2005	2050		
	Base year	REF	LES	LES-Tr	Base year	REF	LES	LES-Tr
Biomass	2%	8%	8%	6%	0%	0%	0%	0%
Coal	0%	0%	0%	0%	485%	362%	385%	448%
Oil	17%	31%	35%	36%	21%	8%	9%	10%
Natural Gas	0%	0%	0%	0%	45%	43%	46%	53%
Oil products	14%	16%	18%	19%	6%	6%	6%	7%
Electricity	0%	0%	0%	0%	10%	10%	10%	12%
Public transportation	3%	2%	2%	2%	2%	2%	2%	2%
Livestock	1%	1%	1%	1%	0%	0%	0%	0%
Agriculture and agroindustry	14%	18%	17%	17%	3%	2%	2%	2%
Energy intensive industry	14%	11%	11%	11%	16%	16%	17%	20%
Rest of Industry	11%	11%	11%	14%	13%	21%	23%	27%
Services	2%	1%	1%	1%	3%	5%	5%	6%